APEM journal

Advances in Production Engineering & Management
Volume 14 | Number 4 | December 2019 | pp 483–493
https://doi.org/10.14743/apem2019.4.343

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Hybrid fuzzy multi-attribute decision making model for evaluation of advanced digital technologies in manufacturing: Industry 4.0 perspective

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A B S T R A C T

Manufacturing is currently at a turning point from mass production to customized production. The implementation of the Industry 4.0 concept, leading to automation and digitalization of manufacturing processes, is therefore considered vital for companies that aim to follow emerging trends in production. Research in this field is primarily focused on companies from developed countries, while companies from transition countries have difficulties to adapt to new business environment. The aim of this paper is to evaluate the use of advanced digital technologies in manufacturing companies from transition countries (i.e. Serbia) in the context of Industry 4.0. To address this problem, an evaluation method based on Fuzzy Analytic Hierarchy Process (FAHP) and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) is proposed. FAHP was used to determine criteria weights as an input for PROMETHEE method which was then used to evaluate advanced digital technologies. For this purpose, the dataset from the European Manufacturing Survey gathered in 2018 from Serbian manufacturing companies is used. The results of this empirical research revealed that production planning and scheduling, digital exchange of data with suppliers/customers, and production control systems play vital role for manufacturers in the context of industry 4.0. These results could serve to manufacturers for their strategic orientation and decision making.

A R T I C L E I N F O

Keywords:
Industry 4.0;
Manufacturing;
Digitalization;
Advanced technologies;
Multi-attribute decision making (MADM);
Fuzzy analytic hierarchy process (FAHP);
PROMETHEE method

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Article history:
Received 10 May 2018
Revised 12 December 2019
Accepted 15 December 2019

1. Introduction

Ever since the beginning of industrialization, technological improvements have led to paradigm shifts which are called industrial revolutions [1]. The fourth industrial revolution (i.e. Industry 4.0) is triggered by the introduction of emerging technologies (e.g., Internet of things, wireless sensor networks, big data, cloud computing, embedded system, and mobile Internet) into the manufacturing environment [2]. The process of introducing Industry 4.0 in manufacturing companies should include the following types of integration [3]:

- Horizontal integration through value networks to facilitate inter-corporation collaboration,
- Vertical integration of hierarchical subsystems inside a factory to create a flexible and reconfigurable manufacturing system,
- End-to-end engineering integration across the entire value chain to support product customization.

Manufacturers that follow these trends should be able to produce customized and small-lot products efficiently and profitably. In order to achieve these standards, advanced digital technologies have become the focus of the research related to Industry 4.0 as they are considered as one of the main enablers of Industry 4.0 [4]. Having this in mind, the "smart factory" is recognized as one of the key features of Industry 4.0 [5]. The smart factory includes following advanced digital technologies:

- Mobile/wireless devices for programming and operation of equipment and machinery [6],
- Digital solutions in production (e.g. tablets, smartphones) [6],
- Software for production planning and scheduling (e.g. ERP) [7],
- Digital exchange of product/process data with suppliers/customers (e.g. supply chain management) [8],
- Near real-time production control system (e.g. systems of centralized operating and machine data acquisition) [9],
- Systems for automation and management of internal logistics (e.g. RFID) [1],
- Product-lifecycle-management-systems [10],
- Virtual reality or simulation [11].

Research related to Industry 4.0 is primarily conducted in manufacturing companies from developed countries, since this concept is developed in leading manufacturing economies of the world [12]. The aim of this research is to evaluate the use of advanced digital technologies in manufacturing companies in the context of Industry 4.0 in transition countries (i.e. Serbia). This evaluation includes a comparison of the aforementioned advanced digital technologies based on a set of criteria. For this purpose, Multi-Criteria Decision Making (MCDM) methods should be used. MCDM problems can be classified into two main categories: Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM). MADM is more appropriate for discrete problems associated with evaluation or ranging of predetermined and limited number of alternatives using a set of criteria. MODM methods are suitable for continuous problems of design or planning, with the aim of achieving aspired goals within given constraints [13]. Since the main concern of this research is to evaluate the use of advanced digital technologies in manufacturing companies, MADM methods will be used, as they are designed to deal with this kind of problems.

MADM methods have emerged as a common tool in research related to manufacturing that involves evaluation procedures. Recently, hybrid MADM methods that combine different MADM methods have become increasingly present in literature. From the range of individual tools, only Analytic Hierarchy Process (AHP) is used more than hybrid MADM methods [14]. Furthermore, hybrid Fuzzy MADM (FMADM) methods are becoming more and more utilized in research. In most cases Fuzzy AHP (FAHP) was combined with other methods (i.e. TOPSIS, VIKOR, and PROMETHEE) [15]. TOPSIS and VIKOR are compromise ranking methods proposed for determining the most preferred alternative based on the closeness to the ideal solution. PROMETHEE method is an outranking method which is based on the pairwise comparison in order to determine the dominance among alternatives [13]. For the evaluation of the use of advanced digital technologies in manufacturing companies it is more important to determine the dominance among alternatives by comparing them to each other, rather than focusing on finding out which of the alternatives is the closest to the ideal solution. Therefore, the PROMETHEE method seems to be more suitable for this research. Similar approach was proposed for selection of organizational innovations in manufacturing companies [16]. Furthermore, the literature review revealed that FAHP [17] and PROMETHEE [18] are primarily used in the research related to manufacturing sector.

In the PROMETHEE method, it is assumed that the decision maker is able to appropriately weight the criteria, as there are no specific guidelines for this procedure. Therefore, it is usually combined with AHP, since it is recommended that PROMETHEE should be strengthened with the ideas of AHP in the phase of determining criteria weights [19]. Furthermore, fuzzy logic was introduced in the procedure of determining criteria weights with AHP to reduce vagueness and uncertainty of the decision-makers' judgement [20].

In this paper, a hybrid FMADM method combining FAHP and PROMETHEE was employed to evaluate the use of advanced digital technologies in manufacturing companies in the context of Industry 4.0. More specifically, the main contribution of this paper is using a hybrid FMADM method combining FAHP and PROMETHEE to evaluate advanced digital technologies in manufacturing companies from transitional countries (i.e. Serbia) that contribute the most to the production principles of Industry 4.0. In this way, the research related to advanced digital technologies in the context of Industry 4.0 will be extended to transitional economies, since current research in this field is typically conducted in manufacturing companies from developed countries.

The remainder of the paper is structured as follows. Section 2 describes the materials, methods and data that were used in this research, while Section 3 presents the research results and discussion. Finally, Section 4 contains the conclusion, including the identified limitations of the study and suggestions for further research.

2. Materials, methods, and data

This work proposes a hybrid FMADM model for evaluating the use of advanced digital technologies in manufacturing companies. More specifically, advanced digital technologies are evaluated in terms of their contribution to the production principles of Industry 4.0. For this purpose, FAHP and PROMETHEE were used. FAHP was applied to determine criteria weights, while PROMETHEE was used for the evaluation of advanced digital technologies. The procedure of the proposed model is presented in Fig. 1.

The AHP method was developed by Saaty [21]. It is based on pairwise comparison using a nine-point scale. The use of crisp numbers for pairwise comparison in traditional AHP is considered insufficient and imprecise due to the vagueness and uncertainty of the decision-makers' judgment [22]. In addition, the opinion of the decision makers is usually expressed in linguistic

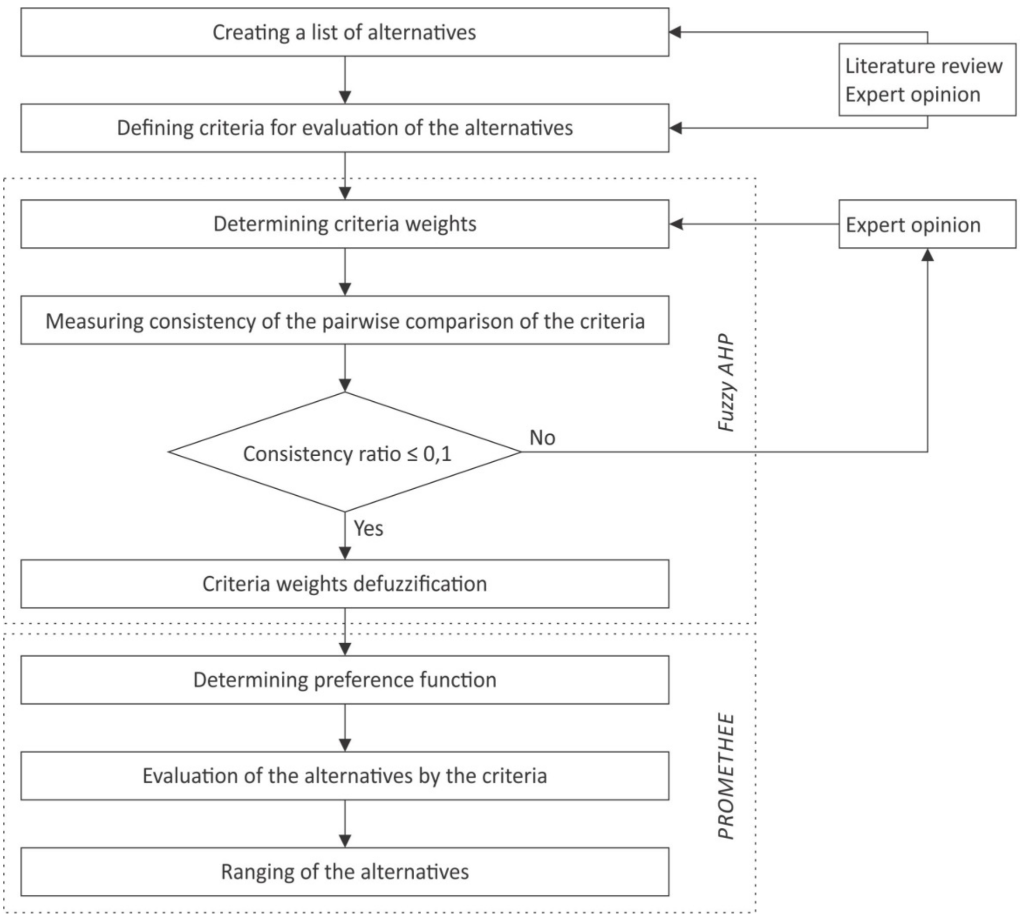

Fig. 1 General model for the evaluation of advanced digital technologies

form. As a result, fuzzy logic was introduced into pairwise comparison process of AHP to reduce this deficiency, as it is designed to deal with the problems concerning subjective uncertainty. Fuzzy set theory is based on the idea that the elements have a degree of membership in a fuzzy set [23]. Fuzzy membership functions (i.e. fuzzy numbers) that featured most often in fuzzy logic are the following: monotonic, triangular, and trapezoidal [24]. Triangular fuzzy numbers (TFNs) are the most utilized in FMADM studies, due to their suitability to the nature of experts' linguistic evaluations [25].

A TFN denoted as $\tilde{a}$ = (*l, m, u*) where $l \leq m \leq u$, has the triangular-type membership function as in Eq. 1:

$$\mu_{\tilde{a}}(x) = \begin{cases} 0, & x < 1 \text{ or } x > u \\ \dfrac{x-l}{m-l}, & l \leq x \leq m \\ \dfrac{u-x}{u-m}, & m \leq x \leq u \end{cases} \tag{1}$$

where *l* and *u* are the lower and upper bounds, and *m* is the most likely value of the fuzzy number $\tilde{a}$.

The procedure of FAHP is as follows:

Step 1. The complex decision-making problem is structured in a hierarchy

Step 2. The linguistic pairwise comparison of criteria is transformed into TFNs $\tilde{a}$ = (*l, m, u*). The linguistic scale used for this purpose along with the corresponding TFNs is shown in Table 1 [26].

Table 1 Membership function of fuzzy numbers

Linguistic scale for importance	Fuzzy number	TFN (l, m, u)	Reciprocal of TFN (1/u, 1/m, 1/l)
Just equal		(1, 1, 1)	(1, 1, 1)
Equal importance	M1	(1, 1, 3)	(0.33, 1, 1)
Weak importance of one over another	M3	(1, 3, 5)	(0.2, 0.33, 1)
Essential or strong importance	M5	(3, 5, 7)	(0.14, 0.2, 0.33)
Very strong importance	M7	(5, 7, 9)	(0.11, 0.14, 0.2)
Extremely preferred	M9	(7, 9, 9)	(0.11, 0.11, 0.14)
Intermediate value between two adjacent judgments	M2, M4, M6, M8		

Step 3. Fuzzy positive reciprocal matrix can be formed based on the information of pairwise comparison as in Eq. 2:

$$\tilde{A}_{n\times n} = \begin{array}{c} \\ 1 \\ \vdots \\ n \end{array} \!\! \begin{array}{c} \begin{array}{ccc} 1 & \cdots & n \end{array} \\ \begin{bmatrix} \tilde{a}_{11} & \cdots & \tilde{a}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \cdots & \tilde{a}_{nn} \end{bmatrix} \end{array}, \qquad a_{ii} = 1, a_{ji} = 1/a_{ij}, a_{ij} \neq 0 \tag{2}$$

Step 4. Fuzzy weights of each criterion are determined as in Eq. 3:

$$\widetilde{w}_i = \tilde{r}_i \times (\tilde{r}_1 + \tilde{r}_2 + \cdots + \tilde{r}_n)^{-1} \tag{3}$$

where (Eq. 4),

$$\tilde{r}_i = (\tilde{a}_{i1} \times \tilde{a}_{i2} \times \cdots \times \tilde{a}_{in})^{1/n} \tag{4}$$

Step 5. Check the consistency of the pairwise comparison judgement. In order to calculate matrix Consistency Ratio (CR), first the matrix Consistency Index (CI) is calculated as in Eq. 5:

$$CI = (\lambda_{max} - n)/(n-1) \tag{5}$$

where λ_{max} is the largest eigenvalue and *n* is the matrix order. After that, CR is calculated as in Eq. 6:

$$CR = CI/RCI \tag{6}$$

where RCI refers to a Random Consistency Index. The RCI with respect to different size matrices can be seen in Table 2.

Table 2 Random Consistency Index

No.	3	4	5	6	7	8	9	10
RCI	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

A CR of 0.1 or less is considered acceptable. If the CR is over the acceptable value, then inconsistency in pairwise comparison judgements has occurred and this process should be reviewed, reconsidered and improved.

Step 6. Defuzzify weights of each criterion. Yager index (Eq. 7) was used for the purpose of weights defuzzification [27]:

$$\tilde{F} = (n - a, n, n + b) = (3n - a + b)/3 \tag{7}$$

Following the procedure of obtaining criteria weights by FAHP, PROMETHEE was implemented for evaluating the use of advanced digital technologies in manufacturing companies in the context of Industry 4.0.

The PROMETHEE method is developed by Brans [28], and it belongs to the family of outranking methods. The majority of researchers refer to PROMETHEE II in their work, as this version of the method is able to provide complete ranking of alternatives [18] compared to PROMETHEE I which is only suitable for partial ranking of alternatives. Two types of information for each criterion are required for the implementation of PROMETHEE II, namely: weight and preference function. Weight determines the importance of each criterion. As previously mentioned, in this paper PROMETHEE II is strengthened by using FAHP to determine criteria weights. Preference function serves to translate the difference between the evaluations obtained by alternatives into a preference degree ranging from zero to one. There are six types of preference functions proposed in PROMETHEE II method: (a) usual criterion, (b) U-shape criterion, (c) V-shape criterion, (d) level criterion, (e) V-shape with indifference criterion, and (f) Gaussian criterion. The procedure of PROMETHEE II method is as follows [28]:

Step 1. Determination of preference function, which translates the difference between the evaluations obtained by two alternatives into a preference degree ranging from zero to one, for each criterion.

Step 2. Determination of deviations based on pairwise comparisons as in Eq. 8:

$$d_j(a, b) = g_j(a) - g_j(b) \tag{8}$$

where $d_j(a, b)$ denotes the difference between the evaluations of a and b on each criterion.

Step 3. Application of the preference function as in Eq. 9:

$$P_j(a, b) = F_j\left[d_j(a, b)\right], \qquad j = 1, \dots, k \tag{9}$$

where $P_j(a, b)$ denotes the preference of alternative a with respect to the alternative b on each criterion, as a function of $d_j(a, b)$.

Step 4. Calculation of an overall or global preference index as in Eq. 10:

$$\forall\, a, b \in A, \qquad \pi(a, b) = \sum_{j=1}^{k} P_j(a, b)\, w_j \tag{10}$$

where $\pi(a, b)$ of a over b (from 0 to 1) is defined as a weighted sum $p(a, b)$ of each criterion, and w_j is the weight associated with the decision maker's preference as the relative importance of the j-th criterion.

Step 5. Calculation of outranking flows as in Eq. 11 and Eq. 12:

$$\phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a, x) \tag{11}$$

$$\phi^-(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a) \tag{12}$$

where $\phi^{+}(a)$ and $\phi^{-}(a)$ represent the positive and negative outranking flow for each alternative, respectively.

Step 6. Calculation of net outranking flow as in Eq. 13:

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a) \tag{13}$$

Step 7. Determine the ranking of all considered alternatives depending on the values of $\phi(a)$. Higher value of $\phi(a)$ implies better ranking of the alternative.

For the purpose of this research, data gathered from European Manufacturing Survey (EMS) are employed. EMS is an international project coordinated by the Fraunhofer ISI Institute from Germany. EMS is a survey focused on modernization and innovation in manufacturing companies taking into account all aspects of a manufacturing process in a standardized and systematized way [29, 30]. The survey is carried out on a triennial basis and considers manufacturing companies (NACE Rev 2 codes from 10 to 33) with more than 20 employees. The dataset used in this paper is built from 2018 data collection conducted among Serbian manufacturing companies. The dataset includes 240 companies of all manufacturing sectors. About 46 % of the companies in the sample are small companies between 20 and 49 employees, another 43 % of the companies have between 50 and 249 employees, and 11 % of the companies have more than 250 employees.

This research employed the part of the EMS survey relating to the use of advanced digital technologies and production characteristics of manufacturing companies. More precisely, the respondents were asked which advanced digital technologies were applied and what the production characteristics in their companies were. The list of advanced digital technologies and production characteristics is the result of expert opinion of EMS consortium members, companies that participated in the research and literature review [1, 16, 31, 32]. The authors have implemented these constructs to build the model, presented in Fig. 2, which was used for evaluation of the use of advanced digital technologies in manufacturing companies in the context of industry 4.0. All dimensions, criteria, and alternatives are summarized in Table 3.

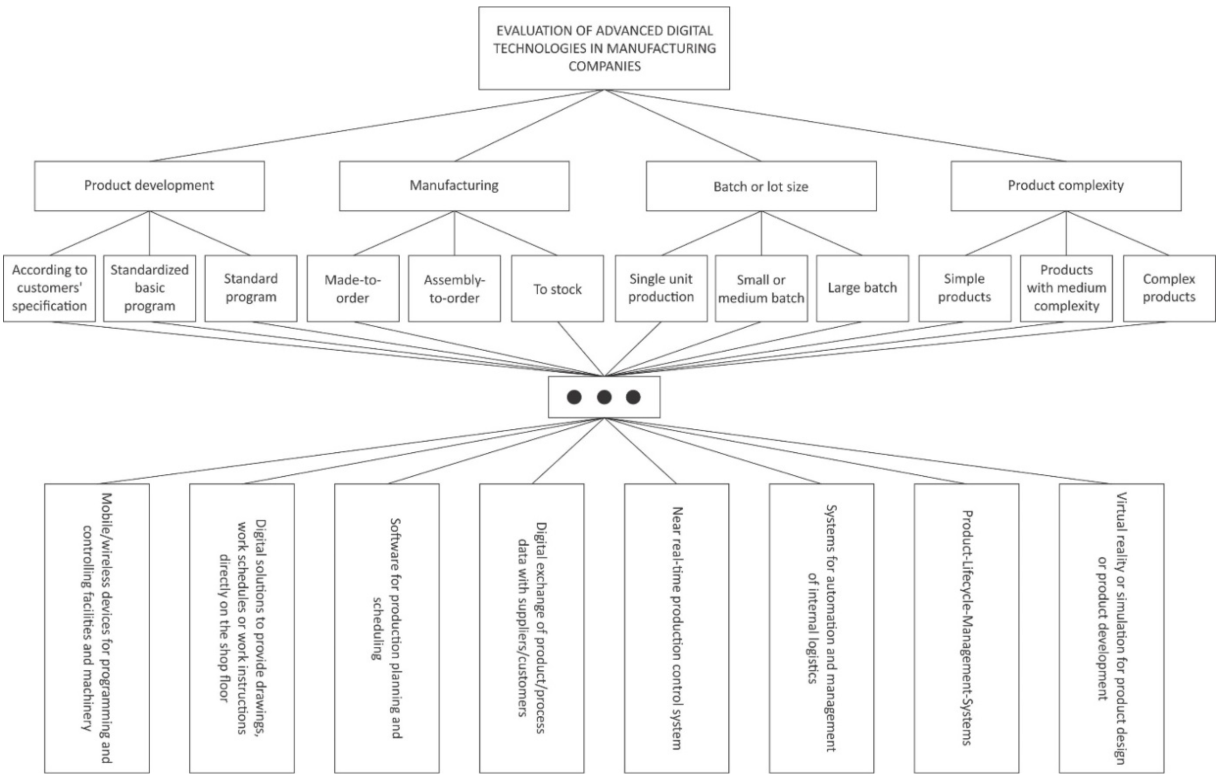

Fig. 2 Model for evaluation of advanced digital technologies in manufacturing companies

Table 3 Dimensions, criteria, and alternatives

Dimensions	Criteria	Alternatives
Product development (D1)	According to customers' specification (C1)	Mobile/wireless devices for programming and controlling facilities and machinery (A1)
	Standardized basic program into which customer specific options are implemented (C2)	Digital solutions to provide drawings, work schedules or work instructions directly on the shop floor (A2)
	Standard program from which the customer can select (C3)	Software for production planning and scheduling (e.g. ERP system) (A3)
Manufacturing (D2)	Made-to-order (C4) Assembly-to-order (C5) To stock (C6)	Digital exchange of product/process data with suppliers/customers (e.g. supply chain management) (A4)
Batch size (D3)	Single unit production (C7) Small or medium batch (C8) Large batch (C9)	Near real-time production control system (e.g. systems of centralized operating and machine data acquisition) (A5)
Product complexity (D4)	Simple products (C10) Products with medium complexity (C11) Complex products (C12)	Systems for automation and management of internal logistics (A6)
		Product-lifecycle-management-systems (A7)
		Virtual reality or simulation for product design or product development (A8)

3. Results and discussion

In this section, the proposed hybrid FMADM method was applied to obtain results. Furthermore, sensitivity analysis was conducted to determine the robustness of the model. Subsequently, the results obtained with the proposed hybrid FMADM method are discussed.

Within the scope of this research eight advanced digital technologies were evaluated based on 12 criteria related to the production characteristics. In the first part of the research, the criteria weights are determined. FAHP was used for this purpose. The results of the pairwise comparison of all dimensions are depicted in Table 4. Subsequently, criteria weights for each dimension (i.e. Product development, Manufacturing, Batch size, and Product complexity) are demonstrated in Tables 5-8, respectively. Following the calculation of criteria weights, consistency of pairwise comparison was checked. The results presented in Table 9 indicate that inconsistency in pairwise comparison procedure is insignificant, since CR is below acceptable value of 0.1 for all dimensions.

Table 4 Pairwise comparison of dimensions (i.e. production characteristics)

Dimensions	D1	D2	D3	D4	Weight
D1	(1, 1, 1)	(1, 1, 3)	(1, 3, 5)	(1, 3, 5)	0.3485
D2	(0.33, 1, 1)	(1, 1, 1)	(1, 3, 5)	(1, 3, 5)	0.3062
D3	(0.2, 0.33, 1)	(0.2, 0.33, 1)	(1, 1, 1)	(0.33, 1, 1)	0.1565
D4	(0.2, 0.33, 1)	(0.2, 0.33, 1)	(1, 1, 3)	(1, 1, 1)	0.1858

Table 5 Pairwise comparison of product development criteria

Criteria (D1)	C1	C2	C3	Local weight	Global weight
C1	(1, 1, 1)	(1, 1, 3)	(3, 5, 7)	0.5275	0.1838
C2	(0.33, 1, 1)	(1, 1, 1)	(1, 3, 5)	0.3447	0.1201
C3	(0.14, 0.2, 0.33)	(0.2, 0.33, 1)	(1, 1, 1)	0.1278	0.0445

Table 6 Pairwise comparison of manufacturing criteria

Criteria (D2)	C1	C2	C3	Local weight	Global weight
C1	(1, 1, 1)	(1, 3, 5)	(3, 5, 7)	0.5972	0.1829
C2	(0.2, 0.33, 1)	(1, 1, 1)	(1, 3, 5)	0.2842	0.0870
C3	(0.14, 0.2, 0.33)	(0.2, 0.33, 1)	(1, 1, 1)	0.1186	0.0363

Table 7 Pairwise comparison of batch size criteria

Criteria (D3)	C1	C2	C3	Local weight	Global weight
C1	(1, 1, 1)	(1, 3, 5)	(1, 3, 5)	0.5547	0.0815
C2	(0.2, 0.33, 1)	(1, 1, 1)	(1, 1, 3)	0.2537	0.0515
C3	(0.2, 0.33, 1))	(0.33, 1, 1)	(1, 1, 1)	0.1917	0.0236

Table 8 Pairwise comparison of product complexity criteria

Criteria (D4)	C1	C2	C3	Local weight	Global weight
C1	(1, 1, 1)	(1, 1, 3)	(1, 3, 5)	0.4643	0.0863
C2	(0.33, 1, 1)	(1, 1, 1)	(1, 3, 5)	0.3602	0.0669
C3	(0.2, 0.33, 1))	(0.2, 0.33, 1)	(1, 1, 1)	0.1756	0.0326

Table 9 Consistency of the pairwise comparison

	Dimensions	Criteria (D1)	Criteria (D2)	Criteria (D3)	Criteria (D4)
CR	0.02	0.03	0.04	0.00	0.02

Table 10 Evaluation matrix

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Min/Max	Max	Max	Max	Max	Max	Max	Max	Max	Max	Max	Max	Max
Weight	0.1838	0.1201	0.0445	0.1829	0.0870	0.0363	0.0815	0.0515	0.0236	0.0326	0.0669	0.0863
Preference function	V-shape	V-shape	V-shape	V-shape	V-shape	V-shape	V-shape	V-shape	V-shape	V-shape	V-shape	V-shape
P value	25	12	8	33	4	8	12	21	17	9	27	9
A1	25	6	1	25	2	5	3	11	12	6	13	11
A2	38	10	9	44	3	10	12	27	17	14	26	15
A3	50	23	14	64	7	16	20	38	32	16	48	21
A4	54	20	10	63	6	14	22	34	29	17	43	22
A5	43	12	6	50	3	10	15	24	25	11	35	15
A6	27	10	5	28	4	8	12	12	18	7	18	13
A7	17	8	4	19	1	7	7	11	11	5	11	10
A8	33	8	4	41	2	3	17	19	10	11	24	10

Table 11 PROMETHEE II method results

Alternative	ϕ	ϕ^+	ϕ^-	Rank
A3	0.7213	0.7294	0.0081	1
A4	0.6821	0.6986	0.0164	2
A5	0.1517	0.3204	0.1687	3
A2	0.0292	0.2466	0.2174	4
A8	-0.1971	0.1404	0.3375	5
A6	-0.2809	0.1075	0.3885	6
A1	-0.5277	0.0222	0.5500	7
A7	-0.5785	0.0133	0.5917	8

Criteria weights determined using FAHP served as an input for evaluation of advanced digital technologies with PROMETHEE II method. All required information for evaluation of advanced digital technologies is given in Table 10. Subsequently, the complete ranking of advanced digital technologies is presented in Table 11.

The results presented in Table 11 indicate the level of contribution of each digital technology included in the model, regarding their role to the production principles of Industry 4.0. In this context, the ranking of technologies is as follows:

- Software for production planning and scheduling (e.g. ERP system),
- Digital exchange of product/process data with suppliers/customers (e.g. supply chain management),
- Near real-time production control system (e.g. systems of centralized operating and machine data acquisition),
- Digital solutions to provide drawings, work schedules or work instructions directly on the shop floor,
- Virtual reality or simulation for product design or product development,
- Systems for automation and management of internal logistics,
- Mobile/wireless devices for programming and controlling facilities and machinery,
- Product-lifecycle-management-systems.

3.1 Sensitivity analysis

Sensitivity analysis of criteria weights is carried out to determine the range (i.e. stability intervals), in which the final ranking of alternatives remains unchanged. The stability intervals for the proposed problem are presented in Table 12. These results show how criteria weights can vary to a certain extent without changing the order of alternatives. Furthermore, it is important to note that all criteria have an impact on the final ranking of alternatives since none of the stability intervals belong to the range from 0 to 1.

Table 12 Stability intervals of criteria

Criteria	Weight	Stability interval	
		Min	Max
C1	0.1838	0.0747	0.3282
C2	0.1201	0.0447	0.2510
C3	0.0445	0.0114	0.1652
C4	0.1829	0.0558	0.3083
C5	0.0870	0.0243	0.2120
C6	0.0363	0.0038	0.1597
C7	0.0815	0.0214	0.1767
C8	0.0515	0.0139	0.1920
C9	0.0236	0.0094	0.1464
C10	0.0326	0.0048	0.1344
C11	0.0669	0.0195	0.1923
C12	0.0863	0.0453	0.2313

3.2 Final remarks

The authors of the current study developed a model for evaluation of the use of advanced digital technologies in manufacturing companies from the perspective of Industry 4.0. FAHP was used to structure the problem, as well as to determine criteria weights. This approach takes into consideration uncertainty and vagueness of human judgement, which is usually involved in decision making process. Moreover, human judgment could lead to inconsistency in MADM models. Therefore, the validity of assigned criteria weights was checked by calculating CR which is far from the acceptable value of 0.1 for all dimensions. Furthermore, sensitivity analysis was conducted in the final stage of the research to additionally confirm quality of criteria weights. On the one hand, the range of stability intervals for each of the criteria shows that the order of alternatives remains the same for certain changes of criteria weights. On the other hand, it was determined that all of the criteria affect the final order of alternatives since none of the stability intervals belong to the range from 0 to 1. These facts lead to the well-founded assumption that the criteria and their assigned weights used in the proposed model are valid. It also justifies the model in terms of robustness. PROMETHEE II was used for the ranking of the alternatives. The quality of the obtain results is guaranteed by flexible preference modelling and the easy use of this method, strengthened with criteria weights obtained by FAHP and the systematic approach in gathering data.

The results presented in Table 11 revealed the great importance of ERP system and Supply Chain Management (SCM) in manufacturing processes concerning production principles of Industry 4.0. The ERP system is considered as a backbone of Industry 4.0 as it plays a vital role in the vertical integration of companies. Moreover, the integration of the ERP system with SCM is recommended for full utilization in the context of Industry 4.0 [33]. Integration of these technologies ensures the appropriate use of products and raw materials in manufacturing processes and the possibility for direct information exchange along the supply chain [34]. Furthermore, as suggested in this research, manufacturers should focus on production control systems. In order to optimize resources in the production chain, efficient real-time production control system combined with reliable analysis of data in production process should be provided [35]. Real-time monitoring of manufacturing processes is considered as one of the key elements for successful implementation of Industry 4.0 concepts [9]. Companies from transitional economies, such as Serbia, should place emphasis on these advanced digital technologies so as to be able to adapt to inevitable changes posed by Industry 4.0.

4. Conclusion

This work investigates the contribution of advanced digital technologies in manufacturing companies in the context of Industry 4.0. For this purpose, a hybrid FMADM model was developed. FAHP was used to structure the problem, as well as to determine importance of different production characteristics, while PROMETHEE II was used to evaluate the use of advanced digital technologies in manufacturing companies within the framework of Industry 4.0. The dataset which formed the basis of this paper was collected through the EMS survey. It has been determined that the ERP system, SCM, and near real-time production control system are the technologies offering the greatest benefits to the production principles of Industry 4.0.

This work contributes to the existing literature by expanding the research related to implementing advanced technologies in the context of Industry 4.0 specifically to transitional economies. In fact, this research sheds light on advanced digital technologies crucial for manufacturers from transitional economies (i.e. Serbia) aiming to introduce the concept of Industry 4.0 into their companies. In this sense, the results presented in this research are of key importance for their strategic orientation.

This research is limited to criteria only related to production characteristics in manufacturing companies. There are other vital criteria linked to Industry 4.0 which are of interest for manufacturing companies that could be included in future research. Furthermore, this work is focused on the use of advanced digital technologies in manufacturing companies. Future research should take into consideration other advanced manufacturing technologies which are considered as enablers of Industry 4.0.

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