Evaluation of advanced digital technologies in manufacturing companies: Hybrid fuzzy MCDM approach

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Abstract

Purpose of this paper is to investigate implementation of advanced digital technologies in manufacturing companies and to evaluate their contribution in the context of Industry 4.0 in transition countries (i.e. Slovenia, Croatia, and Serbia). Data taken from European Manufacturing Survey are used for this research. Fuzzy Analytic Hierarchy Process (FAHP) was employed to determine criteria weights, while Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) was employed to rank advanced digital technologies. Software for production planning and scheduling, near real-time production control systems and supply chain management contribute the most to manufacturing companies interested in production principles of Industry 4.0.

Keywords: Digital manufacturing, FAHP, PROMETHEE

Introduction

Ever since the beginning of industrialization, technological advancement and improvements have led to paradigm shifts which are named industrial revolutions (Lasi et al., 2014). Recently, the emerging technologies (e.g., Internet of Things, wireless sensor networks, big data, cloud computing, embedded system, and mobile Internet) are being introduced into the manufacturing environment, which is leading to the fourth industrial revolution (Wang et al., 2016). With the fourth industrial revolution (i.e. Industry 4.0) manufacturing processes have become increasingly complicated, but also automated and sustainable.

In the process of introducing Industry 4.0 companies should make a minimum of three basic types of integration: Horizontal integration through value networks to facilitate inter-corporation collaboration; Vertical integration of hierarchical subsystems inside a factory to create flexible and reconfigurable manufacturing system; End-to-end engineering integration across the entire value chain to support product customization (Kagermann et al., 2013).

Industry 4.0 will lead to certain changes in organization of manufacturing companies due to changing operative framework conditions. Particularly, these changes are triggered by the following trends: individualization on demand, flexibility, decentralization, short development periods, and resource efficiency (Lasi et al., 2014). Therefore, manufacturers that follow these trends should be able to produce customized and small-lot products efficiently and profitably.

Advanced digital technologies are in the focus of Industry 4.0. Therefore, most of the studies are focusing on technological innovations in manufacturing companies (Droege et al., 2009). Also, research related to Industry 4.0 is mainly conducted in developed countries. It is rather expected since this concept is invented in leading manufacturing economies of the world (Oesterreich & Teuteberg, 2016). Purpose of this paper is to investigate implementation of advanced digital technologies in manufacturing companies and to evaluate their contribution in the context of Industry 4.0 in transition countries (i.e. Slovenia, Croatia, and Serbia).

Decision making process becomes more difficult in such a complex environment. Inevitable changes in manufacturing sector will lead to the problem of selecting the best option from a wide range of alternatives based on a set of criteria. Multiple criteria decision making (MCDM) is the process of finding the best option from all of the feasible alternatives in the presence of multiple, usually conflicting criteria (Zanakis et al., 1998).

In this paper, hybrid fuzzy MCDM (FMCDM) method combining Fuzzy Analytic Hierarchy Process (FAHP) (P.J.M. van Laarhoven and W. Pedrycz, 1983) and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) (Brans 1982) was used to determine which advanced digital technologies are more suitable for manufacturing companies that are streaming towards the concept of Industry 4.0. The main contribution of this paper is to employ hybrid FMCDM method combining FAHP and PROMETHEE to select advanced digital technologies in manufacturing companies that are contributing the most to the production principles of Industry 4.0. In this way, the scope of the possible implementation area for the proposed method will be widened. In addition, most of the research related to advanced digital technologies is conducted on companies from developed countries. This paper will bring some perspective on implementation of advanced digital technologies in manufacturing companies from transition countries.

The remainder of the paper is structured as follows. Literature review is presented in Section 2. Section 3 describes the proposed method that has been used in this paper, while Section 4 presents the research results and discussion. Finally, Section 5 presents the conclusion of this paper with identified limitations of the study and suggestions for further research.

Literature review

This part of the paper is divided into two segments equally important for the research. The first one is dedicated to the concept of industry 4.0, while the second one is related to implementation of MCDM methods in manufacturing.

Industry 4.0

The concept Industry 4.0 was developed by the German Federal Government to promote its High-tech strategy (Oesterreich & Teuteberg, 2016). The similar terms were also introduced in other main industrial countries – “Industrial Internet” in the United States and “Internet +” in the People's Republic of China (Wang et al., 2016).

From the technical point of view, Industry 4.0 can be described as the increasing digitization and automation of the manufacturing environment and creation of a digital value chain to enable communication between products and their environment and business partners. One of the fundamental concepts of Industry 4.0 is “smart factory” (Lasi et al. 2014). Smart factory includes following technological concepts: Software for production planning and scheduling (e.g. ERP) (Klöpper et al., 2012); Systems for automation and management of internal logistics (e.g. RFID) (Lasi et al., 2014); New systems in the development of products and services (Lucke et al., 2008); Product-Lifecycle-Management-Systems (PLM) (Tchoffa et al., 2016); Mobile/wireless devices for programming and operation of equipment and machinery (Drath & Horch, 2014); Digital solutions in production (e.g. tablets, smartphones) (Drath & Horch, 2014).

MCDM Methods in Manufacturing

MCDM methods have emerged as a popular tool in research related to manufacturing, especially hybrid MCDM methods. From individual tools, only AHP is used more than hybrid MCDM methods (Mardani et al., 2015). Recently, hybrid FMCDM methods are becoming more and more utilized. It is reported that in most cases FAHP was combined with other methods. The most commonly used methods in combination with FAHP are: PROMETHEE, TOPSIS, VIKOR, ANP, ELECTRE, and DEMATEL (Mardani et al., 2015).

Based on the literature review, it was found that FAHP is primarily used in the manufacturing sector (Kubler et al., 2016). In the same manner, it was determined that manufacturing is one of the most important application areas of PROMETHEE method as well (Behzadian et al., 2010).

In PROMETHEE method, it is assumed that the weights of criteria are defined by the decision maker. Therefore, it is usually combined with AHP to improve the evaluation performance. It is suggested that PROMETHEE method should be strengthened with the ideas of AHP (Macharis et al., 2004). There are various examples of this hybrid MCDM method in literature. For example, AHP was used to assign criteria weights and PROMETHEE to determine net advantages of reconfigurable schemes for reconfigurable manufacturing systems (Wang et al., 2017). Also, AHP and PROMETHEE were integrated for the subcontractor selection problem (Polat, 2016). In the same manner combined AHP and PROMETHEE were used for equipment selection in manufacturing (Dağdeviren, 2008). Combination of AHP and PROMETHEE has been used in previous research. Nevertheless, to the best of our knowledge, no research has been conducted to assess it in the context of Industry 4.0 and advanced digital technologies.

Methodology and data

This paper proposes hybrid FMCDM method combining FAHP and PROMETHEE for selection of advanced digital technologies that are moving manufacturing companies towards production principles of Industry 4.0. More specifically, this method is applied in the context of manufacturing companies from transition countries. FAHP was used to determine the importance of criteria and PROMETHEE was used to rank alternatives. Survey method research was used to gather necessary data for analysis.

Fuzzy AHP

AHP method was proposed by Saaty (Saaty, 1980). It uses hierarchical structure to evaluate alternatives based on various criteria. AHP is based on pair-wise comparison using nine-point scale. The use of crisp numbers in traditional AHP seems insufficient and imprecise due to the vagueness and uncertainty of decision-makers' judgment. Also, decision makers usually express their opinion in linguistic form. As a result, fuzzy logic was introduced into pairwise comparison process of AHP to reduce this deficiency.

Fuzzy set theory was first introduced by Zadeh (Zadeh, 1965). It was designed to deal with the problems concerning subjective uncertainty. Subjective uncertainty arises in cases in which linguistic variables are used to represent a problem (Hwang & Yoon, 1981). This is especially important for MCDM problems where decision makers often use linguistic variables to express their opinion about certain problems. Fuzzy set theory is based on the idea that the elements have a degree of membership in a fuzzy set (Zimmermann, 1985). Monotonic, triangular, and trapezoidal fuzzy membership functions (i.e. fuzzy numbers) are the most commonly used in fuzzy logic (Taha & Rostam, 2011). Triangular fuzzy numbers (TFNs) are the most utilized in fuzzy MCDM studies, due to their computational simplicity (Giachetti & Young, 1997) and suitability to the nature of experts' linguistic evaluations (Patil & Kant, 2014).

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

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

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 linguistic pairwise comparison of criteria is transformed into TFNs $\tilde{a} = (l, m, u)$. For this purpose, linguistic scale with corresponding TFNs is introduced (Table 1).

Table 1 – Membership function on fuzzy numbers (Anojkumar et al., 2014)

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 2: Based on the information of pairwise comparison, fuzzy positive reciprocal matrix can be formed as in Equation (2):

$$\tilde{A}_{n\times n} = \begin{matrix} & 1 & \cdots & n \\ 1 & \tilde{a}_{11} & \cdots & \tilde{a}_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ n & \tilde{a}_{n1} & \cdots & \tilde{a}_{nn} \end{matrix}, a_{ii} = 1, a_{ji} = 1/a_{ij}, a_{ij} \neq 0$$

Step 3: Determine fuzzy weights of each as in Equation (3):

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

where (Equation 4):

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

Step 4: Check the consistency of the pairwise comparison judgment. In order to identify matrix Consistency Ratio (CR), first the matrix Consistency Index (CI) is identified as in Equation (5):

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

Where λ_{max} is the largest eigenvalue and n is the matrix order. After that, CR is identified as in Equation (6):

$$CR = CI/RCI$$

where RCI refers to a Random Consistency Index. The RCI with respect to different size matrices is presented 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 CR is over the acceptable value, then inconsistency in pairwise comparison judgments has occurred and this process should be reviewed, reconsidered, and improved.

Step 5: Defuzzify weights of each criterion. For the purpose of weights defuzzification Yager index was used (Yager, 1981) (Equation 7):

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

Consequently, obtained weights from FAHP can be used for ranking of advanced digital technologies by PROMETHEE.

PROMETHEE

The PROMETHEE family of outranking methods, including the PROMETHEE I for partial ranking of the alternatives and the PROMETHEE II for complete ranking of the alternatives, were developed by Brans (Brans, 1982). PROMETHEE II is described in this part of the paper, since majority of researchers have referred to this version of the method (Behzadian et al., 2010). This method is based on a pairwise comparison of alternatives in respect to each defined criterion. The implementation of PROMETHEE II requires two types of information. Decision maker needs to define weight and preference function for each criterion. Weight determines the importance of each criterion. In this paper FAHP was used to determine weights for criteria. Preference function serves to translate difference between the evaluations obtained by alternatives into a preference degree ranging from zero to one. There are six types of preference functions proposed: usual criterion, U-shape criterion, V-shape criterion, level criterion, V-shape with indifference criterion and Gaussian criterion. The procedure of PROMETHEE II method is as follows:

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 Equation (8):

$$d_j(a,b) = g_j(a) - g_j(b)$$

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 Equation (9):

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

Where $P_j(a,b)$ denotes the preference of alternative a with regard 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 Equation (10):

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

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 expressing of the decision maker's preference as the relative importance of the j-th criterion.

Step 5: Calculation of outranking flows as in Equations (11) and (12), respectively:

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

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

Where $\Phi^{+}(a)$ and $\Phi^{-}(a)$ denote the positive outranking flow and negative outranking flow for each alternative, respectively.

Step 6: Calculation of net outranking flow as in Equation (13):

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

Step 7: Determine the ranking of all the considered alternatives depending on the values of $\Phi(a)$. Higher value of $\Phi(a)$, means better ranking of the alternative. Thus, the best alternative is the one having the highest $\Phi(a)$value.

Sample and data collection procedure

The proposed hybrid FMCDM method was applied for selection of advanced digital technologies that are moving manufacturing companies towards production principles of Industry 4.0. For this purpose, survey was conducted to gather necessary information. Data collection process was part of the international project European Manufacturing Survey (EMS), which is coordinated by Fraunhofer ISI Institute from Germany. For the purpose of our analysis Slovenian, Croatian, and Serbian dataset were used. EMS is a survey on manufacturing strategies, production and product characteristics, and the use of advanced digital technologies in production (Lalic et al., 2017). The survey was conducted among manufacturing firms (NACE Rev 2 codes from 10 to 33) having at least 20 employees. The dataset includes 474 firms of all manufacturing industries. About 33.1% of the firms in the sample are small firms between 20 and 49 employees, another 50.6% of the firms have between 50 and 249 employees, and 16.3% of the firms have more than 250 employees.

Results and discussion

In this section, proposed hybrid FMCDM method was applied to obtain results. Subsequently, results obtained with proposed hybrid FMCDM method are discussed.

Results of the study

In this study, we evaluated 8 advanced digital technologies based on 12 criteria. Criteria are related to the type of production and product characteristics in manufacturing companies. All dimensions, criteria, and alternatives are presented in Table 3. To obtain data necessary for evaluation of advanced digital technologies respondents were asked which advanced digital technologies they use in their company. They were also asked about the type of production and product characteristics as indicated in criteria for evaluation. As mentioned before, FAHP was used to determine the weights of criteria. Subsequently, PROMETHEE was used to rank advanced digital technologies. Local weights of criteria were calculated first. Assumption was made that all dimensions have equal importance (0.25). Based on this assumption, global weights for criteria were determined. Since all pairwise comparisons are done in the same manner, only the comparison for criteria belonging to the first dimension is presented in the paper (Table 4). Consistency of pairwise comparison judgments was checked. CR=0.07 < 0.1 gives us confidence that there was no inconsistency in pairwise comparison judgments. All necessary information for ranking of the alternatives is presented in Table 5. Subsequently, complete ranking of alternatives is presented in Table 6.

Table 3 – Dimensions, criteria and alternatives

Dimensions	***Criteria***	***Alternatives***
Product development (D1)	According to customers' specification (C1)	Software for production planning and scheduling (A1)
	Standardized basic program into which customer specific options are implemented (C2)	Near real-time production control system (A2)
	Standard program from which the customer can select (C3)	Digital Exchange of product/process data with suppliers / customers (A3)
Manufacturing (D2)	Made-to-order (C4)	Systems for automation and management of internal logistics (A4)
	Assembly-to-order (C5)	Mobile/wireless devices for programming and operation of equipment and machinery (A5)
	To stock (C6)	Product-Lifecycle-Management-System (A6)
Batch size (D3)	Single unit production (C7)	Technologies for safe human-machine interaction (A7)
	Small or medium batch (C8)	Digital solutions for providing drawings, work schedules or work instructions directly on the shop floor (A8)
	Large batch (C9)	
Product complexity (D4)	Simple products (C10)	
	Products with medium complexity (C11)	
	Complex products (C12)	

Table 4 – Pair-wise comparison of criteria

Criteria (D1)	C1	C2	C3	Local weights	Global weights
C1	(1, 1, 1)	(1, 3, 5)	(5, 7, 9)	0.6311	0.1578
C2	(0.2, 0.33, 1)	(1, 1, 1)	(1, 3, 5)	0.2711	0.0678
C3	(0.11, 0.14, 0.2)	(0.2, 0.33, 1)	(1, 1, 1)	0.0978	0.0244

Table 5 – 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	0.1578	0.0678	0.0244	0.1578	0.0678	0.0244	0.1578	0.0678	0.0244	0.1578	0.0678	0.0244
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	29	22	16	48	6	15	10	29	30	19	32	17
A1	55	42	26	93	11	26	18	61	52	33	63	29
A2	37	39	29	71	11	25	17	41	43	33	45	22
A3	28	26	21	52	9	19	14	30	36	20	37	22
A4	22	21	18	46	7	15	8	27	28	15	34	13
A5	11	13	9	20	4	8	7	17	7	7	16	6
A6	14	14	7	26	2	10	7	18	15	13	16	9
A7	17	14	13	36	7	6	4	23	19	12	23	9
A8	18	20	11	34	5	14	11	23	17	22	22	8

Table 6 – Ranking of alternatives with PROMETHEE method

Alternative	Φ	Φ^+	Φ^-	Rank	Alternative	Φ	Φ^+	Φ^-	Rank
A1	0.7550	0.7550	0.0000	1	A8	-0.2158	0.0175	0.2332	5
A2	0.4640	0.4810	0.0171	2	A7	-0.2789	0.0088	0.2877	6
A3	0.1387	0.2057	0.0670	3	A6	-0.3372	0.0000	0.3372	7
A4	-0.1621	0.0271	0.1893	4	A5	-0.3637	0.0000	0.3637	8

According to the results (Table 6), 3 out of 8 advanced digital technologies have positive net outranking flow (Φ value). Therefore, these 3 technologies can be considered as more important than other for manufacturing companies that are streaming towards the concept of Industry 4.0. It should be emphasized that other advanced digital technologies have their importance for manufacturing companies as well, but in this context they have less influence. With respect to their ranking, important advanced digital technologies for manufacturing companies are as follows:

- Software for production planning and scheduling (e.g. ERP system)
- Near real-time production control system (e.g. systems of centralized operating and machine data acquisition)
- Digital Exchange of product/process data with suppliers/customers (e.g. supply chain management)

ERP system is considered as a backbone of Industry 4.0 because of its role in vertical integration of companies. It is suggested that ERP system should be integrated with supply chain management for full utilization in the context of Industry 4.0 (Haddara & Elragal 2015). This integration of advanced digital technologies ensures appropriate use of products and raw materials in manufacturing processes and the possibility for direct information exchange with suppliers (Sajko et al. 2013). Efficient real-time production control system and analysis of data in production process should be ensured to optimize resources in the production chain (Zhou et al. 2016). Real-time monitoring of manufacturing processes is considered as one of the key elements for successful implementation of Industry 4.0 concepts (Shafiq et al. 2016).

Conclusion

Fourth industrial revolution has brought new ways of doing business. All types of integration are becoming an important factor for companies in order to stay competitive on the globalized market. Industry 4.0 introduces advanced technologies which present one of the key elements of open, complex and smart industry. Manufacturing companies are trying to adapt to market changes by introducing customized and complex products.

This paper examines importance of advanced digital technologies for the manufacturing companies in transition countries in the context of Industry 4.0. For this purpose, hybrid FMCDM method was proposed. FAHP was employed to determine the weights of criteria, while PROMETHEE was employed to rank the alternatives. The data used in this paper are gathered through the EMS survey. It was determined that ERP system, near real-time production control system and supply chain management contribute the most to the production principles and product characteristics related to Industry 4.0 concept.

This paper contributes to the existing literature by widening the area in which FAHP based PROMETHEE can be used. There is a lack of research investigating advanced digital technologies in the context of Industry 4.0 in transition countries. More specifically, there is no research proposing combination of hybrid FMCDM and survey research to deal with this kind of issues.

This research is limited only to criteria related to types of production and product characteristics. There are other criteria, which are important for manufacturing companies that could be included in future research. Also, this research considers only the use of digital technologies in manufacturing companies. Future research should take into consideration other advanced manufacturing technologies as well.

Acknowledgment

This work is supported by funding of **Croatian Science Foundation O-1861-2014 – 3535** Building competitiveness of Croatian Manufacturing.

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