Designating Industry 4.0 Maturity Items and Weights for Small and Medium Enterprises

Araştırma Makalesi/Research Article

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Abstract— The vision of Industry 4.0 is an integrated ecosystem in supply chain where every item and human in the plant has an ID in production and works without any external intervention, communicating with each other in every operation. Although such a concept of manufacturing may sound futuristic to many companies, and especially SMEs, the transition to this future is inevitable, and organizations need a roadmap to clearly understand the concepts and effectively execute the applications of Industry 4.0. In this paper, the level of importance of each Industry 4.0 criterion for SMEs is expressed and used to develop a quantitative maturity model. Analytic Hierarchy Process was utilized to calculate the weights of dimensions and maturity items. An iterative procedure led to 9 different dimensions and 33 correlated items. Initial findings showed that the "Strategy and Organization" dimension has the highest impact on maturity level along with the items "Manufacturing Software", "Employees", and "Industry 4.0 Roadmap".

Keywords— industry 4.0, maturity model, analytic hierarchy process, industry 4.0 index

Küçük ve Orta Ölçekli İşletmeler için Endüstri 4.0 Olgunluk Öğeleri ve Ağırlıklarının Belirlenmesi

Özet— Endüstri 4.0'ın vizyonu, tedarik zincirinde tesisteki her bir öğenin ve insanın üretimde bir kimliğe sahip olduğu ve herhangi bir işlemde birbirleriyle iletişim kurarak herhangi bir dış müdahale olmaksızın çalıştığı entegre bir ekosistemdir. Böyle bir üretim kavramı birçok şirkete, özellikle de KOBİ'lere fütüristik gelse de, bu geleceğe geçiş kaçınılmazdır ve kuruluşlar, kavramları açıkça anlamak ve Endüstri 4.0 uygulamalarını etkili bir şekilde yürütmek için bir yol haritasına ihtiyaç duyarlar. Bu makalede, her bir Endüstri 4.0 kriterinin KOBİ'ler için önem seviyesi ifade edilmiş ve nicel bir olgunluk modeli geliştirmek için kullanılmıştır. Boyutların ve olgunluk öğelerinin ağırlıklarının hesaplanmasında Analitik Hiyerarşi Süreci kullanılmıştır. Çalışma kapsamında 9 farklı boyut ve 33 ilişkili öğe belirlenmiştir. İlk bulgular, "Strateji ve Organizasyon" boyutunun "Üretim Yazılımı", "Çalışanlar" ve "Endüstri 4.0 Yol Haritası" öğeleriyle birlikte olgunluk seviyesi üzerinde en yüksek etkiye sahip olduğunu göstermiştir.

Anahtar Kelimeler— endüstri 4.0, olgunluk modeli, analitik hiyerarşi süreci, endüstri 4.0 endeksi

1. INTRODUCTION

The world economy and industry evolve over time to adapt to changes in society and human needs, producing advancements in technology that have a significant impact on both society and industry. The industrial revolution began in Britain with mechanization and became a full-fledged, all-encompassing transition from handmade production to machines. The first machines, such as the textile loom, which was powered with steam and water, gave way to the next step of the revolution, which was powered by the widespread use of electricity, and which led mass production to become a phenomenon ubiquitous in the satisfaction of the world population's increasing demands. After the introduction of computers into our lives, automation systems took over in industry, and PLC (programmable logic controller) systems and robots started to be utilized. As history amply demonstrates, revolutions in industry are not usually radically new concepts, but rather improvements in technology that shape how industry operates and production systems work. The latest industrial phase has been referred to as the fourth industrial revolution, the so-called “Industry 4.0”, according to the German government.

Pioneer in the field of digitization and industrial solution, Pricewaterhouse Coopers (PwC) describes Industry 4.0 as an end-to-end digitization of all cyber-physical systems from product to plant where digital integration within the value chain plays a critical role [1]. In order to best utilize this digital transformation and gain the maximal benefits from Industry 4.0, companies must understand specific concepts related to these developments. The German government defines the framework of Industry 4.0 as having 9 pillars: Internet of Things(IoT), cybersecurity, additive manufacturing, augmented reality, big data and analytics, simulation, horizontal and vertical integration, autonomous robots and cloud computing. Despite of this well definition, each industry and business are different from one another and positioned at a different technological level in the context of digitization.

Although the concept of digitized manufacturing may sound ridiculous and futuristic to many companies, the transition to digitization is inevitable. Thus, organizations, particularly SMEs, need a roadmap to clearly understand the concepts involved and effectively implement the applications of Industry 4.0, i.e., smart factories and smart products. Our observations and interviews with managers and experts have shown that many businesses lack sound knowledge of Industry 4.0 and digitization despite the media’s ongoing emphasis of these changes and what is at stake. But it is essential for SMEs to acquire the skills to transition, as inculcating the new concepts into a company’s existent culture is complicated without the adequate tools.

Maturity models, readiness tests, and frameworks have been exploited to understand the position and development of a company in a specific area [2]. Industry 4.0 maturity models have been presented in the literature based on various scopes, dimensions, items, and maturity levels. There is, for example, an Industry 4.0 maturity model focused on large scaled engineering companies [3]. Since there is a gap between large companies and SMEs in terms of access to financial instruments and their starting point in terms of digitization [4], these models have a long way to go to meet the SMEs needs. There are ongoing research and developments in maturity models focusing on SMEs [5,6,7]. However, the development processes of the models are ambiguous, and the importance of each maturity item and dimension remains unknown.

Assessing Industry 4.0 is a complex undertaking in which criteria and sub-criteria are intertwined and can be misjudged by many in society, even by experts. Such an assessment is challenging because it must produce a determination of the weights of maturity items and dimensions. In the literature, however, only one study has taken into account the weights of maturity items and dimensions, though in that study the calculation and designation of the weights were unmentioned [8]. Therefore, an analytical and scientific approach is required to determine the correct maturity items and calculate the weights.

Analytic Hierarchy Process (AHP) was developed by Thomas L. Saaty in 1978 to solve complex scenarios involving multiple criteria in the decision-making process by approaching the problem from pairwise comparison of each element [9]. The model has been used for over 4 decades in many fields from manufacturing to healthcare [10,11]. In industry, the AHP method was demonstrated to successfully evaluate suppliers along environmental factors [12], and also to provide a lean assessment of an organization [13]. Assembly line balancing and optimization are related subjects of Industry 4.0. Line balancing and importance of relative costs have been determined in a recent study via AHP technique [14]. In another study, an iteration of AHP has been combined with another method called Preference Ranking Organization Method for Enrichment Evaluations to evaluate items in Industry 4.0 perspective; however, it is relatively complex and reflects slightly restricted opinion based on a survey [15]. AHP presents a qualitative approach toward determining the weight of each factor in a multi-criteria environment.

To the best of our knowledge, there is no study seeking to establish Industry 4.0 maturity items by applying AHP to calculate the weight of each item precisely. Therefore, in this paper, our aim is to determine Industry 4.0 maturity items and dimensions for SMEs by following a scientific process and using AHP successfully to derive the weights.

2. METHODOLOGY

This research utilizes an iterative and proven procedure to develop maturity models in IT management, which is based on a thorough literature review, including comparisons of maturity models in the field and expert reviews [16]. Although Becker’s procedure is to develop a complete maturity model, in this study only the first phases were adapted to determine Industry 4.0 dimensions and maturity items. Overall, the two phase procedure is depicted in Figure 1.

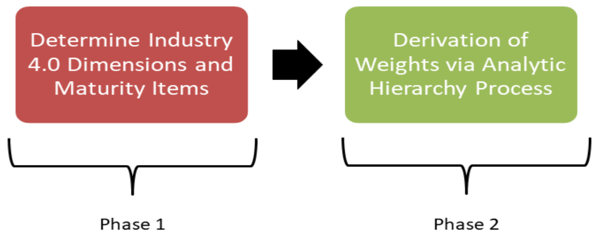


Figure 1. Overall research methodology

2.1. Determining the Industry 4.0 Dimensions and Maturity Items

We conducted a comprehensive literature review using a technique developed by Tranfield et al. [17]. This method is promising in the field of management and has already been used in research related to Industry 4.0 and SMEs [18]. Keywords were selected and a literature review was conducted in Web of Science and Google Scholar databases within the fields of title, keywords, and abstract:

i. 'industry 4.0' AND 'maturity model'
ii. 'industry 4.0' AND 'roadmap'
iii. 'industry 4.0' AND 'readiness'
iv. 'smart manufacturing' AND 'maturity model'
v. 'smart manufacturing' AND 'roadmap'
vi. 'smart manufacturing' AND 'readiness'

As of the date of research, including the years 2013, 2014, 2015, 2016, 2017, and 2018, a total of 109 results were found. Following a detailed examination of abstracts and removing the irrelevant and repetitive papers, nine maturity models were ultimately obtained.

Industry 4.0 maturity dimensions were obtained from these studies, and the corresponding maturity items were selected considering the requirements of digitization in SMEs. After the first draft was developed, expert reviews were conducted to eliminate unnecessary items, and finally relevant maturity items were determined for further weight derivation. The summary of the methodology followed in this phase is summarized in Figure 2.

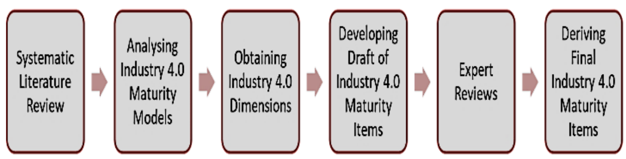


Figure 2. First phase flow diagram

2.2. Deriving Weights Using AHP

Industry 4.0 maturity items are complex and interwoven together, and are occasionally misjudged by enterprises. As an example of the situation, it is hard to think about cloud computing and big data separate from data analytics. Also, the utilization of the industrial internet of things with many connected devices raises additional concerns about cybersecurity where potential data leaks potentially harm the business. Analytic Hierarchy Process (AHP) is a simple method to deal with this complicated scenario employing pairwise comparison of each item in a matrix using Saaty's comparison scale as shown in Table 1 [9].

Table 1. AHP comparison scale [9]

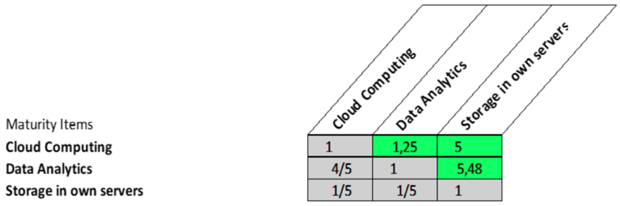
Importance	Definition
1/9	Extremely less important
1/8	Intermediate Value
1/7	Very Considerably Less Important
1/6	Intermediate Value
1/5	Considerably Less Important
1/4	Intermediate Value
1/3	Moderately Less Important
1/2	Intermediate Value
1	Equally Important
2	Intermediate Value
3	Moderately More Important
4	Intermediate Value
5	Strongly More Important
6	Intermediate Value
7	Very Strongly More Important
8	Intermediate Value
9	Extremely Important

A step-by-step AHP methodology applied in this study is as following:

i. Developing pairwise comparison matrices
ii. Calculating normalized matrices
iii. Calculating eigenvectors
iv. Measuring consistency of weights

First, AHP was applied to nine main criteria, and then nine AHP were applied separately for sub items to ten experts. The geometric mean of the results was used to develop the pairwise comparison matrix. In this study, ten different pairwise comparison matrices were developed, including, separately, the dimensions' maturity items. An Excel worksheet was designed to gather data from the experts of Information and Communication Technology (ICT), including academicians, managers and specialists with at least ten years of expertise in the manufacturing sector and SMEs. Experts are comprised of ICT managers, industrial engineers, system and data analysts.

The geometric mean of ten respondents was calculated to derive the comparison matrices. Pairwise comparison demonstrates the importance of rows against columns. An example of a pairwise comparison matrix is shown in Figure 3.



Maturity Items	Cloud Computing	Data Analytics	Storage in own servers
Cloud Computing	1	1,25	5
Data Analytics	4/5	1	5,48
Storage in own servers	1/5	1/5	1

Figure 3. A geometric mean of pairwise comparison matrix of maturity items belonging to dimension-data processing and storage

Notice that this is a reciprocal comparison matrix and considering the element of a_{ij}, the lower diagonal a_{ji} can be calculated in equation (2.1). In the example in Figure 3, a_{11} is the level of importance of 'cloud computing' against 'data anlytics'.

$$a_{ji} = \frac{1}{a_{ij}} \quad \textbf{(2.1)}$$

In other words, pairwise comparison matrix is shown in equation (2.2).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ . & & & . \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad \textbf{(2.2)}$$

Using the equation (2.3), in next step, matrix A can be normalized.

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad \textbf{(2.3)}$$

The normalized matrix containing elements of b_{ij} is shown in equation (2.4).

$$N = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ . & & & . \\ b_{n1} & b_{n2} & \dots & b_{nn} \end{bmatrix} \quad \textbf{(2.4)}$$

The next step, Priority vector, which is the normalized eigenvector of the N matrix, can be calculated by taking the arithmetic mean of row elements according to equation (2.5). The Priority vector indicates the weights of each compared criterion.

$$w_i = \frac{\sum_{j=1}^{n} b_{ij}}{n} \quad \textbf{(2.5)}$$

From the calculated w_i, W column vector, also known as the Priority vector, is obtained as shown in equation (2.6). The elements of this Priority vector, w_i, represent the weight of each corresponding item.

$$W = \begin{bmatrix} w_1 \\ w_2 \\ . \\ . \\ . \\ w_n \end{bmatrix} \quad \textbf{(2.6)}$$

Finally, the consistency of pairwise comparison via AHP is highly subjective and related to the answers given by experts. In order to measure this consistency, Saaty (1978) came up with the Consistency Index (CI). If the answers given during comparison are fully consistent, the CI should be 0. However, such a result is exceedingly unlikely in the real world of practice. In this study, the CI was calculated using equation (2.7).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \textbf{(2.7)}$$

λ_{max} is the corresponding eigenvalue of calculated W eigenvector and can be derived using equation (2.8).

$$A \,.\, w = \lambda_{max} \,.\, w \quad \textbf{(2.8)}$$

To calculate consistency ratio, CR, CI should be compared with an index acquired randomly, also known as a random index. This random index, RI, is related to the number of compared items as shown in Table 2 [19]. Thus, CR is calculated via equation (2.9).

$$CR = \frac{CI}{RI} \quad \textbf{(2.9)}$$

Table 2. Matrix scale – RI relation [19]

Number of Items	RI
1	0
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

3. RESULTS & DISCUSSION

3.1. Industry 4.0 Dimensions and Maturity Items

The systematic literature review and the process stated in Chapter 2.1 revealed Industry 4.0 maturity model dimensions and items as summarized in Table 3. 33 items are grouped under nine dimensions. It is important to note that their distributions are not even.

Table 3. Industry 4.0 dimensions and maturity items

Dimensions	Maturity Items
Strategy and Organization [20,3,21,8]	Industry 4.0 roadmap
	Lean manufacturing
	Agile manufacturing
	Innovation management
	Financing and budget
	Supply chain management
Employees [3,8]	Team designated to Industry 4.0
	IT competence of employees
	IT department
	Leadership skill
Smart Production [22]	Data gathering from machine/human
	Autonomous systems
	Digital modelling
	Artificial Reality(AR)/Virtual Reality(VR) Technologies
Manufacturing Technologies and Systems [3]	Rapid prototyping (3-D Printing and Additive Manufacturing)
	Computer aided design/manufacturing (CAD/CAM)
	Manufacturing Software (Manufacturing Execution System (MES), Enterprise Resource Planning (ERP), etc.)
Information and Communication Technology Infrastructure [7,21]	Communication and network systems
	Mobile technologies
	Utilization of RFID, NFC, and Barcode
Vertical and Horizontal Integration [7,23]	Horizontal integration with customers
	Horizontal integration with suppliers
	Vertical integration within company
Industrial Internet of Things [23,24]	Interaction between things
	Data flow from the product
	Additional functionalities to the product (GPS, self-reporting, integration, product memory, etc.)
Cybersecurity [23,25]	Data security policy
	Threat of cyber crimes
	Back-up system
	Data security software
Data Processing and Storage [26,3]	Cloud computing
	Data analytics
	Storage in own servers

3.2. Weights of Industry 4.0 Dimensions and Maturity Items

Following the methodology stated in Chapter 2.2, AHP was utilized to obtain the weights of each dimension, (g); then, nine different pairwise comparison matrices were developed to calculate the weights of each maturity item (w), as summarized in Table 4.

Table 4. Weights of industry 4.0 maturity model dimensions and items

Dimensions	Weights of Dimensions (g)	Items	Weights of Items (w)	Total Weights (t) [g x w]
Strategy and Organization	0.247	Industry 4.0 roadmap	0.347	0.086
		Lean manufacturing	0.115	0.029
		Agile manufacturing	0.111	0.027
		Innovation management	0.083	0.020
		Financing and budget	0.226	0.056
		Supply chain management	0.118	0.029
Employees	0.150	Team designated to Industry 4.0	0.331	0.050
		IT competence of employees	0.248	0.037
		IT department	0.204	0.031
		Leadership skill	0.217	0.032
Smart Production	0.085	Data gathering from machine/human	0.540	0.046
		Autonomous systems	0.247	0.021
		Digital modelling	0.108	0.009
		AR/VR technologies	0.105	0.009
Manufacturing Technologies and Systems	0.116	Rapid prototyping	0.275	0.032
		Computer aided design/manufact uring	0.192	0.022
		Manufacturing software	0.533	0.062
Information and Communication Technology Infrastructure	0.104	Communication and network systems	0.537	0.056
		Mobile technologies	0.254	0.027
		Utilization of RFID, NFC, and Barcode	0.209	0.022
Vertical and Horizontal Integration	0.072	Horizontal integration with customers	0.293	0.021
		Horizontal integration with suppliers	0.294	0.021
		Vertical integration within company	0.413	0.030
Industrial Internet of	0.058	Interaction between things	0.379	0.022

Things		Data flow from the product	0.419	0.024
		Additional functionalities to the product	0.202	0.012
Cybersecurity	0.076	Data security policy	0.553	0.042
		Threat of cyber crimes	0.143	0.011
		Back-up system	0.174	0.013
		Data security software	0.130	0.010
Data Processing and Storage	0.090	Cloud computing	0.482	0.044
		Data analytics	0.430	0.039
		Storage in own servers	0.088	0.008

The total weights of each item (t) can be calculated according to the equation (3.1), where i indicates the number of dimensions and j indicates the number of items within a dimension. For example, t_{12} indicates "Lean Manufacturing".

$$t_{ij} = g_i \, x \, w_{ij} \quad \textbf{(3.1)}$$

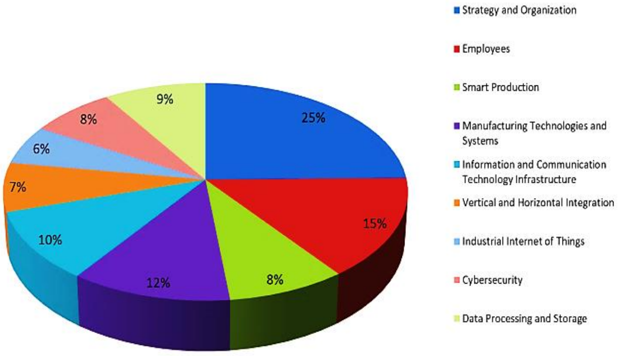


Figure 4. Weight comparison of industry 4.0 maturity dimensions

As is depicted in Figure 4, in terms of dimension, the results indicate that "Strategy and Organization" has the highest impact with 25%, followed by "Employees" and "Manufacturing Technologies and Systems", at 15% and 12%, respectively. Interestingly, although Industry 4.0 is referred to synonymously as IoT, SMEs believe that the "Industrial Internet of Things" has the least importance among all dimensions. This may be explained by the fact that the motives within IoT are not well understood and accepted by SMEs, a problem whose rectification can be considered as a long term goal in the transformation to Industry 4.0.

Regarding the total weights of all maturity items, (t), a detailed comparison is visualized incrementally in Figure 5.

"Industry 4.0 Roadmap" is the leading factor for SMEs. Thereafter, subsequent to "Manufacturing Software", "Communication and Network Systems" and "Financing and Budget" follow. It is obvious that Industry 4.0 maturity is a process of organizational change within an enterprise necessitating a good starting point with vision and strategy. Similar results were also reported in another study [8].

Additionally, the fact that "Manufacturing Software" is the second important item indicates that SMEs put an emphasis on Enterprise Resource Planning (ERP) and Manufacturing Execution System (MES) in the digitization process that should be taken into account before investing in infrastructure. Considering the fact that ERP and MES are the framework of data flow and reporting within a smart factory, this result was an expected outcome. SMEs' prioritization of the manufacturing software has also been reported before [18].

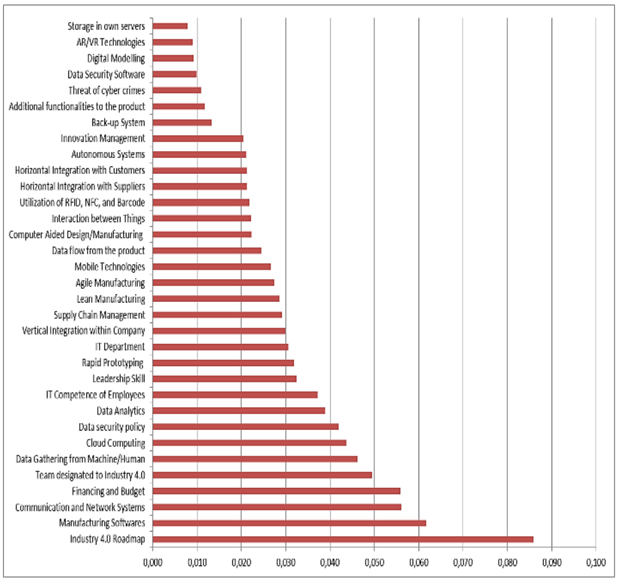


Figure 5. Weight comparison of industry 4.0 maturity items

One other salient criterion is "Financing and Budget", an outcome underlining that a dedicated budget and financial sustainability are required for SMEs to succeed in digitization as they transition to Industry 4.0. Today, the enabling technologies of Industry 4.0, such as RFID systems, automation robots, and communication infrastructure have become cheaper. Nonetheless, such technologies can be costly in unplanned circumstances. Considering the fact that SMEs struggle more in finance management compared to large scale enterprises [4], proper budgeting and dedicating adequate financial tools and solutions at the beginning are essential to succeed in Industry 4.0 transformation projects.

In terms of level of importance, "Storage in Own Servers" has the lowest impact, whereas "Cloud Computing" is more than five times more important. This indicates that SMEs put a high emphasis on cloud technology and services in their transition to Industry 4.0.

Table 5. Consistency ratio of AHP matrices

Dimensions	Consistency Ratio (CR)
Strategy and Organization	0.026
Employees	0.098
Smart Production	0.066
Manufacturing Technologies and Systems	0.003
Information and Communication Technology Infrastructure	0.025
Vertical and Horizontal Integration	0.018
Industrial Internet of Things	0.019
Cybersecurity	0.063
Data Processing and Storage	0.016
Overall Consistency of Dimensions	**0.038**

The consistency analysis of the study is summarized in Table 5. As it is stated earlier, ten different AHP pairwise comparison matrices have been developed to investigate overall dimensions and each items related to specific dimensions. According to the calculations, all CR values are less than 0.1 which indicates that the geometric comparison matrices are consistent and AHP results are applicable [9]. CR values tend to be high when relatively a large number of criteria are compared; however, overall consistency of dimensions indicates that the AHP is highly consistent even with nine criteria.

4. CONCLUSION

The urge to industrialize is the priority for the majority of governments and enterprises throughout the world. Still, the concepts of Industry 4.0 are misjudged and often cause confusion even for authorities and experts. Considering the complications involved in the transition to Industry 4.0, maturity models are necessary to observe the process and assess the stage in the process at which organizations find themselves.

In this study, an iterative maturity model developing methodology was followed based on a systematic literature review. Additionally, expert opinions were collected and together with the former were used to obtain the dimensions and items reflecting Industry 4.0 maturity among SMEs. 33 maturity items were gathered under nine dimensions with both technological and social aspects. The weights of each dimension and related items were calculated by AHP, the usage of which brings a quantitative approach to the discussion of maturity models. Results showed that “Strategy and Organization” is the most important factor in SMEs’ maturity in Industry 4.0.

It is important to note that AHP is an intuitional method in which the pairwise comparison is significantly related to the subjective judgments. In this research, ten experts from different fields in manufacturing and the academy contributed to AHP. However, for further studies, we suggest to increase the number of experts in order to achieve broader deductions. Experts from various fields of manufacturing industry can lead to different item weights since the importance of each item slightly diverge in other sectors.

It is possible to build on the maturity items and weights derived in this research to continue in the development of a complete analytic maturity model containing maturity levels and type of assessment as well. The findings of this study are important for the further development of Industry 4.0 maturity models for SMEs, and assist in narrowing the gap between large scale enterprises and SMEs on their way toward Industry 4.0.

REFERENCES

[1] PricewaterhouseCoopers, **Industry 4.0 : Building the digital enterprise,** 1-36, 2016.

[2] T. Mettler, "Maturity assessment models: a design science research approach", *Int J Soc Syst Sci*, 3, 81-98, 2011.

[3] K. Lichtblau, V. Stich, R. Bertenrath, M. Blum, M. Bleider, A. Millack, K. Schmitt, E. Schmitz, M. Schröter, **Impuls - Industrie 4.0 Readiness,** Aachen, Cologne, 2015.

[4] S. Mittal, M. A. Khan, D. Romero, T. Wuest, "A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs)", *J Manuf Syst*, 49, 194–214, 2018.

[5] J. Ganzarain, N. Errasti, "Three Stage Maturity Model in SME’ s towards Industry 4.0", *J Ind Eng Manag*, 9, 1119–1128, 2016.

[6] K. Jung, B. Kulvatunyou, S. Choi, M. P. Brundage, "An overview of a smart manufacturing system readiness assessment", *IFIP Advances in Information and Communication Technology*, 488, 705–712, 2017.

[7] C. Leyh, T. Schäffer, K. Bley, S. Forstenhäusler, "Assessing the it and software landscapes of industry 4.0-enterprises: The maturity model SIMMI 4.0", **Lecture Notes in Business Information Processing**, Springer, Cham, 103–119, 2017.

[8] A. Schumacher, S. Erol, W. Sihn, "A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises", *Procedia CIRP*, 52, 161–166, 2016.

[9] T. L. Saaty, "Modeling unstructured decision problems - the theory of analytical hierarchies", *Math Comput Simul*, 20, 147–158, 1978.

[10] S. Sipahi, M. Timor, "The analytic hierarchy process and analytic network process: An overview of applications", *Manag. Decis.*, 48, 775–808, 2010.

[11] C. Çetinkaya , M. Kabak, E. Özceylan , "3D Printer Selection by Using Fuzzy Analytic Hierarchy Process and PROMETHEE", *Bilişim Teknolojileri Dergisi*, 10(4), 371-380, 2017.

[12] R. Handfield, S. V. Walton, R. Sroufe, S. A. Melnyk, "Applying environmental criteria to supplier assessment: A study in the application of the Analytical Hierarchy Process", *Eur J Oper Res*, 141, 70–87, 2002.

[13] A. Azadeh, M. Zarrin, M. Abdollahi, S. Noury, S. Farahmand, "Leanness assessment and optimization by fuzzy cognitive map and multivariate analysis", *Expert Syst Appl*, 42, 6050–6064, 2015.

[14] L. Nagy, T. Ruppert, J. Abonyi, "Analytic Hierarchy Process and Multilayer Network-Based Method for Assembly Line Balancing", *Appl. Sci.*, 10, 3932, 2020.

[15] N. Medić, Z. Anišić, B. Lalić, U. Marjanović, M. Brezočnik, "Hybrid fuzzy multi-attribute decision making model for evaluation of advanced digital technologies in manufacturing: Industry 4.0 perspective", *Advances in Production Engineering & Management*, 14(4), 483-493, 2019.

[16] J. Becker, R. Knackstedt, J. Pöppelbuß, "Developing Maturity Models for IT Management", *Bus Inf Syst Eng*, 1, 213–222, 2009.

[17] D. Tranfield, D. Denyer, P. Smart, "Towards a methodology for developing evidence-informed management knowledge by means of systematic review", *British Journal of Management*, 14, 207-222, 2003.

[18] A. Moeuf, R. Pellerin, S. Lamouri, S. Tamayo-Giraldo, R. Barbaray, "The industrial management of SMEs in the era of Industry 4.0", *Int J Prod Res*, 56(3), 1118-1136, 2018.

[19] R. W. Saaty, "The analytic hierarchy process—what it is and how it is used", *Math Model*, 9, 161–176, 1987.

[20] K. Y. Akdil, A. Ustundag, E. Cevikcan, "Maturity and Readiness Model for Industry 4.0 Strategy", **Industry 4.0: Managing The Digital Transformation**, Springer, Cham, 61–94, 2018.

[21] PricewaterhouseCoopers, **Industry 4.0 - Enabling Digital Operations Self Assessment**, 2016.

[22] A. Kermer-Meyer, "Industry 4.0 Maturity Assessment", **Hannover Messe 2017**, Hannover, Germany, 1–9, 2017.

[23] M. Rüßmann, M. Lorenz, P. Gerbert, M. Waldner, J. Justus, P. Engel, M. Harnisch, **Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries**, The Boston Consulting Group, 2015.

[24] J. Wan, S. Tang, Z. Shu, D. Li, S. Wang, M. Imran, A. V. Vasilakos, "Software-Defined Industrial Internet of Things in the Context of Industry 4.0.", *IEEE Sens J*, 16, 7373–7380, 2016.

[25] D. Wu, A. Ren, W. Zhang, F. Fan, P. Liu, X. Fu, J. Terpenny, "Cybersecurity for digital manufacturing", *J Manuf Syst.*, 48, 3-12, 2018.

[26] E. Gökalp, U. Şener, P. E. Eren, "Development of an Assessment Model for Industry 4.0: Industry 4.0-MM", **Software Process Improvement and Capability Determination**, vol 770. Editör: Mas A., Mesquida A., O'Connor R., Rout T., Dorling A., Springer, Cham, 128–142, 2017.