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Optimisation of the relationship between structural parameters of the processing industry as a way to increase its efficiency

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ABSTRACT
Industry, which on average accounts for about 60% of commodity exports in the EU-28, with over 58% resulting from the processing industry, plays a key role in ensuring the competitiveness of EU countries. The article aims to simulate the influence of structural processing industry parameters on the industry's efficiency. Correlation methods and the regression analysis were used to substantiate the hypotheses regarding the effect that the share comprised of high-tech and medium-high-tech industries has on the output structure, and the impact made by the share of imports in the intermediate consumption of those industries on the efficiency (the share of gross value added (GVA) in output) of the processing industry. Based on the criteria indicating the increased technological level and reduced import dependence, economic and mathematical models of optimisation were created for the output structure and intermediate consumption of the processing industry, which were then solved using the linear programming method. The authors present the mathematical proof of the relationship between the change in structural parameters (shares of high-tech and medium-tech industries and the share of imports in the structure of their intermediate consumption) of the processing industry and the ratio of the gross value added/output. The results of the simulation, which were based on data from the European Statistical Office and the Organization for Economic Cooperation and Development, provide an analytical basis for selecting industrial policy benchmarks.

KEY WORDS
processing industry structure, efficiency, gross value added, share of output, share of imports, intermediate consumption, optimisation

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Introduction

The deepening globalisation has had a generally positive impact on economic development, and in particular, foreign trade; however, it also intensified competition in the world market. Under such conditions, the industrial sector plays a key role in ensuring the competitiveness of EU countries, as it accounts for about 60% of commodity exports on average in the EU-28, with over 58% resulting from the processing industry. The processing industry is the manufac-

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turing sector, in which enterprises use physical or chemical processes to transform materials, substances or components into new products. According to the European Classification of Economic Activities NACE Rev.2, processing covers 33 industries, which can be classed into the following groups: food, woodworking, textile, chemical, oil refining, metallurgy, engineering, furniture, repair, and installation of machinery and equipment.

Since industrial enterprises produce about 50% of intermediate consumption products, their results determine the external trade balance of EU countries as well as the state of their economy in general. Industry — and primarily its processing sector — remains the leading economic activity, which can be evidenced by intensified reshoring processes in developed EU countries. However, a high level of efficiency must be achieved to maintain competitiveness or the enduring ability to withstand competition with the help of the available potential. This largely depends on the existing structural parameters, by which this study understands the relationship between the shares of different types of industry (based on the level of manufacturability — high-tech, medium-high-tech, moderately-low-tech and low-tech) in output of the processing industry.

This article is a logical continuation and further extension of research results aspiring to actualise the problematic issues arising from the functioning of the industrial sector of the economy, particularly aimed at finding and justifying ways for increasing the efficiency of the processing industry in EU countries and creating appropriate optimisation models.

The article intends to simulate the influence made by structural parameters of the processing industry on the industry's efficiency. This problem statement follows from previous studies made by the authors of this article. As hypothesised by Ishchuk (2018) and Sozanskyy (2018a, 2018b), the relationship between the structural parameters of the processing industry significantly affects the efficiency (namely, share of GVA in output). This hypothesis was confirmed by the results of research conducted in the Ukrainian processing industry. Based on this hypothesis, the authors used their original economic and mathematical model (Ishchuk, 2018; Sozanskyy, 2018b) to optimise the structure of the Ukrainian industrial production to the level of Poland using the criteria for increasing efficiency and manufacturability.

However, the question arises regarding the relevance of the hypothesis, the applied methodological approach and the developed economic and mathematical model for other countries, especially in the EU, which differ in terms of economic scale and specialisation of the processing industry. This study is also relevant because of the issue of structural transformations in the economy in general and the industrial sector in particular, as well as the expediency to use optimisation models, which has been the subject of many other studies.

For example, Wlodarczyk (2013) presented an overview of structural changes in the Polish food industry over the period 2000–2012 and the optimisation of the structure of production factors using nonlinear programming methods. The optimisation of the sectoral structure of economic resources to maximise Turkey's income using linear programming methods was described in detail by Can (2012) and Atlan (2016). Čapek (2016) used the dynamic stochastic general equilibrium (DSGE) model and Bayesian methods to present an estimation of structural changes in the Czech economy over the period 1996–2002. Taušer (2015) used the autoregressive distributed lag (ADL) model to demonstrate a high correlation between the Czech exports and the German GDP as well as the significant integration of the Czech and German economies. Olczyk (2017) applied the sectorial approach and the error correction model to assess the international competitiveness of the Czech industry. This facilitated conclusions regarding the significant dependence of Czech exports on imported components.

Vogstad (2009) offered a broad overview of the possibilities and examples to apply linear programming methods as well as input-output data tables in resource optimisation processes. Tan et al. (2019) presented models for optimising interconnections between industry sectors to improve export and import tactics. And Sharify (2018) discussed the theoretical and methodological principles for the application of the nonlinear supply-driven input-output model.

However, the available studies paid insufficient attention to modelling the impact made by structural parameters of the processing industry on the industry's efficiency, and especially to the comparison of different countries. Research on this topic rarely includes a comprehensive scientific approach that covers the entire spectrum from problem argumentation and the proposal as well as confirmation of hypotheses to their justification and testing by models, formulation of scientific and analytical conclusions and recommendations that could be potentially applied in the realm of the real economy. Also, researchers rarely use the information capabilities of input-output tables, specifically in the assessment of the degree of import dependence particular to economic sectors.

1. Research method

The authors of the article used the results of thorough analytical studies into the industrial sector of the economy of three selected countries (Poland, Germany and the Czech Republic) to hypothesise that a higher share of high-tech and medium-high-tech industries in the structure of processing industry's output results in a higher share of GVA in output for this type of industrial activity. However, this hypothesis was fully empirically confirmed only for Poland and Germany as the results of correlation-regression analysis established the existence of a stochastic and linear relationship, which was very close to deterministic, and a direct relationship between changes in the studied parameters. This hypothesis was not fully confirmed for the Czech processing industry due to a relatively low closeness of the relationship between the change in the selected parameters. These conclusions resulted in further detailed studies of the Czech processing industry, which served as the basis for the second hypothesis, stating that a lower share of imports in the intermediate consumption of high-tech and medium-high-tech industries results in a higher share of GVA in the processing industry's output. This hypothesis was empirically confirmed by the results of the correlation-regression analysis, which showed the presence of a close stochastic relationship and the inverse relationship between changes in the studied parameters.

The formulated and confirmed hypotheses became the methodological basis for optimising the structure of the processing industry in Poland and the Czech Republic according to the criteria of an increasing level of manufacturability and reducing import dependence. The target function of the optimisation was the efficiency index of the German processing industry, which is the industry leader in the EU. Determinative multiplicative models were used for optimisation because of a functional relationship between the share of GVA in output and the selected structural parameters. Actual data (structural indicators of the industry of the studied countries) was used to test the mathematical adequacy of the models. As linear programming methods allow the most accurate solutions for optimisation tasks, they were used to solve the models. As discussed in the literature overview, these arguments have been confirmed by modelling results of the economic processes of different countries.

Data for analytical assessments were sourced from the European Statistical Office (2016, 2019), the United Nations Industrial Development Organization (2019) and the Organization for Economic Cooperation and Development (OECD), including input-output tables and national accounts. The methodological basis of the research included general scientific, economic-logical and economic-mathematical methods of economic analysis, in particular such methods as cognition theory, deterministic factor and general analysis, correlation-regression analysis, and linear programming.

The following text presents the algorithm for solving the tasks, as well as the most important results of the authors' in-depth analytical research on the formation and confirmation of hypotheses, the elaboration and solution of optimisation models.

Having similar industrial potential parameters, Poland and Germany are among the most industrialised countries of the EU. In 2017, Poland exceeded Germany by 9.18 percentage points (pp) (45.53% vs 36.35%) in terms of the level of industrialisation (the share contributed by industry to gross domestic product (GDP)); whereas in 2014, Poland was in the lead only by 1.1 pp (37.74% vs 36.64%). In absolute numbers of output and GVA, the Polish industry was inferior to the German in 2017, respectively by 6.41 and 5.80 times, while in 2014, the differences between the values amounted to 6.64 and 7.26 times. At the same time, by share of GVA in output (which is one of the main indicators of the economic efficiency), the German industry has had a constant advantage (≈4 pp) over the Polish industry with 34.57 % vs 30.49% in 2017 (33.69% vs 29.90% in 2014).

One of the main reasons for such differences is the relatively lower efficiency of the Polish processing industry. Thus, by share of GVA in the processing industry's output in 2017, Poland was inferior to Germany by 7.05 pp. The German processing industry exceeded the Polish in all high-tech and medium-high-tech industries without exception, and so it did in 2017, in the vast majority of other industries, based on this indicator of efficiency (Table 1). The Polish processing industry had insignificant advantages in two low-tech (manufacture of textiles, wearing apparel, leather and related products; and manufacture of wood, paper, printing and reproduction) and

Tab. 1. Share of gross value added in the processing industry's output in 2017 (%)

The group	The manufacturing	Classification code of economic activities NACE Rev. 2	Poland	Germany
The high-tech	Manufacture of basic pharmaceutical products and pharmaceuticals	C21	32.40	53.64
	Manufacture of computers, electronic and optical products	C26	17.51	45.96
The medium-high-tech	Manufacture of chemicals and chemical products	C20	26.17	32.90
	Manufacture of electrical equipment	C27	22.08	41.01
	Manufacture of machinery and equipment not elsewhere classified	C28	32.30	37.94
	Manufacture of motor vehicles, trailers and semi-trailers	C29	20.26	33.41
	Manufacture of other transport equipment	C30	31.42	32.70
The moderately-low-tech	Manufacture of coke and refined petroleum products	C19	16.03	10.37
	Manufacture of rubber and plastic products	C22	28.84	35.19
	Manufacture of other non-metallic mineral products	C23	34.90	36.77
	Manufacture of basic metals	C24	17.77	19.96
	Manufacture of fabricated metal products, except machinery and equipment	C25	34.99	41.15
	Repair and installation of machinery and equipment	C33	48.11	36.06
The low-tech	Manufacture of food products; beverages and tobacco products	C10-12	23.67	23.75
	Manufacture of textiles, wearing apparel, leather and related products	C13-15	35.62	32.88
	Manufacture of wood, paper, printing and reproduction	C16-18	30.91	30.07
	Manufacture of furniture; other manufacturing	C31-32	32.66	45.09
Total processing industry			**27.01**	**34.06**

Source: elaborated by the authors based on Eurostat data (Eurostat, 2016).

two medium-low-tech industries (manufacture of coke and refined petroleum products; and repair and installation of machinery and equipment).

Hence it follows, that a higher economic efficiency of the German processing industry (as compared to the Polish) can be explained by its greater orientation towards high-tech industries and industries with a higher degree of raw material processing. This thesis was confirmed by the comparison of GVA and output structures of processing industries in these two countries (Table 2).

Thus, the share of high-tech and medium-high-tech industries in the output structure of the German processing industry is 1.8 times larger than in Poland. The German processing industry is founded on medium-high-tech industries that comprise 51.04%, of which 21.14% is the production of motor vehicles, trailers and semitrailers. Meanwhile, the Polish processing industry is supported on low-tech industries that amount to 35.21%, of which 19.89% is the manufacture of food products, drinks and tobacco products.

In the case of Poland and Germany, a close relationship exists between the dynamics particular to the share of high-tech and medium-high-tech industries in the structure of the processing industry's output on the one hand, and the share of GVA in the processing industry's output on the other. During the studied period, both Poland and Germany saw the increase in the share of medium-high-tech industries in the structure of the processing industry's output, which concurred with the increase in the share of GVA in the processing industry's output (Figs. 1 and 2). The exception was the post-crisis year 2010 in Poland.

The correlation and regression analysis established a stochastic and linear correlation, which was very close to functional (deterministic), since the correlation coefficients between the studied indicators for Poland and Germany were very high, respectively, 0.91 and 0.92 (Figs. 3 and 4). The values for the coefficient of determination (R) show that in the analysed period, share of GVA in the Polish and German processing industry's output depended on the share (total) of high-tech and medium-high-tech industries in the structure of the processing industry's output by 83.20% and 84.64%, respectively.

Thus, an analytical review and results of the correlation and regression analysis of Poland and Germany confirmed the hypothesis stating that a higher share of high-tech and medium-high-tech industries in the structure of the processing industry's output

Tab. 2. Structures of gross value added and output of the processing industries in Poland and Germany in 2017 (%)

The group	The manufacturing	Classification code of economic activities NACE Rev.2	The structure of gross value added		The output structure	
			Poland	Germany	Poland	Germany
The high-tech	Manufacture of basic pharmaceutical products and pharmaceuticals	C21	1.58	3.33	1.32	2.12
	Manufacture of computers, electronic and optical products	C26	2.09	6.08	3.22	4.50
	Total		**3.67**	**9.41**	**4.54**	**6.62**
The medium-high-tech	Manufacture of chemicals and chemical products	C20	4.93	7.47	5.09	7.73
	Production of electric equipment	C27	3.69	6.72	4.52	5.58
	Manufacture of machinery and equipment not elsewhere classified	C28	4.64	15.41	3.88	13.84
	Production of motor vehicles, trailers and semitrailers	C29	8.77	20.74	11.69	21.14
	Manufacture of other transport equipment	C30	2.08	2.64	1.79	2.75
	Total		**24.11**	**52.98**	**26.96**	**51.04**
The moderately-low-tech	Production of coke and coke products of oil refining	C19	3.16	0.82	5.32	2.71
	Manufacture of rubber and plastic products	C22	7.76	4.47	7.27	4.32
	Manufacture of other non-metallic mineral products	C23	5.70	2.65	4.41	2.46
	Metallurgical production	C24	2.82	3.09	4.29	5.27
	Manufacture of fabricated metal products, except machinery and equipment	C25	11.56	8.45	8.92	6.99
	Repair and installation of machinery and equipment	C33	5.48	2.30	3.07	2.18
	Total		**36.48**	**21.78**	**33.29**	**23.93**
The low-tech	Manufacture of food products; beverages and tobacco products	C10-12	17.43	6.93	19.89	9.94
	Manufacture of textiles, wearing apparel, leather and related products	C13-15	3.42	1.15	2.59	1.19
	Manufacture of wood, paper, printing and reproduction	C16-18	8.94	3.79	7.81	4.29
	Manufacture of furniture; other manufacturing	C31-32	5.95	3.96	4.92	2.99
	Total		**35.73**	**15.83**	**35.21**	**18.41**
Total processing industry			**100.00**	**100.00**	**100.00**	**100.00**

Source: elaborated by the authors based on Eurostat data.

results in a higher share of GVA in output generated by this type of industrial activity. It follows that the optimisation of the processing industry structure (in terms of particular industries) is a way to increase the industry's efficiency.

The authors developed an economic and mathematical model to optimise the structure of processing industry's output using the criterion for increasing efficiency (i.e., achieving the desired share of GVA in output). The optimisation model (1) is deterministic and reflects a functional relationship (i.e., the changing value of one indicator inevitably results in the changing value of another) that exists between the dynamics particular to shares of output held by individual industries and characteristic to the processing industry's GVA on the one hand, and the change in share of GVA in the processing industry's output on the other:

$$\frac{q}{p} = \frac{q_1 + q_2 + \ldots + q_{17}}{p_1 + p_2 + \ldots + p_{17}} = \frac{q\left(\frac{q}{q}\right)\left(\frac{q_1}{q} + \frac{q_2}{q} + \ldots + \frac{q_{17}}{q}\right)}{p\left(\frac{p}{p}\right)\left(\frac{p_1}{p} + \frac{p_2}{p} + \ldots + \frac{p_{17}}{p}\right)} \rightarrow opt, \quad (1)$$

where:
q – the gross value added of the processing industry;
p – the output of the processing industry;
$q_1, q_2, \ldots, q_{17}$ – the gross value added of 17 industries of the processing industry;
$p_1, p_2, \ldots, p_{17}$ – the output of 17 industries of the processing industry;
$\frac{q_1}{q}, \frac{q_2}{q}, \ldots, \frac{q_{17}}{q}$ – the shares of 17 industries in GVA of the processing industry;
$\frac{p_1}{p}, \frac{p_2}{p}, \ldots, \frac{p_{17}}{p}$ – the shares of 17 industries in the output of the processing industry.

The target function of the optimisation is the increase in the actual value of share of GVA in the processing industry's output up to the desired level.

For an elaborated optimisation model (1), a set of criteria and constraints was defined as follows:

- The sum of the shares of individual 17 industries comprising the output and GVA structures of the processing industry is 1:

$$\frac{q_1}{q} + \frac{q_2}{q} + \ldots + \frac{q_{17}}{q} = 1; \quad \frac{p_1}{p} + \frac{p_2}{p} + \ldots + \frac{p_{17}}{p} = 1 \qquad (2)$$

- The values of share of GVA in output for each of the 17 industries of the processing industry should grow.

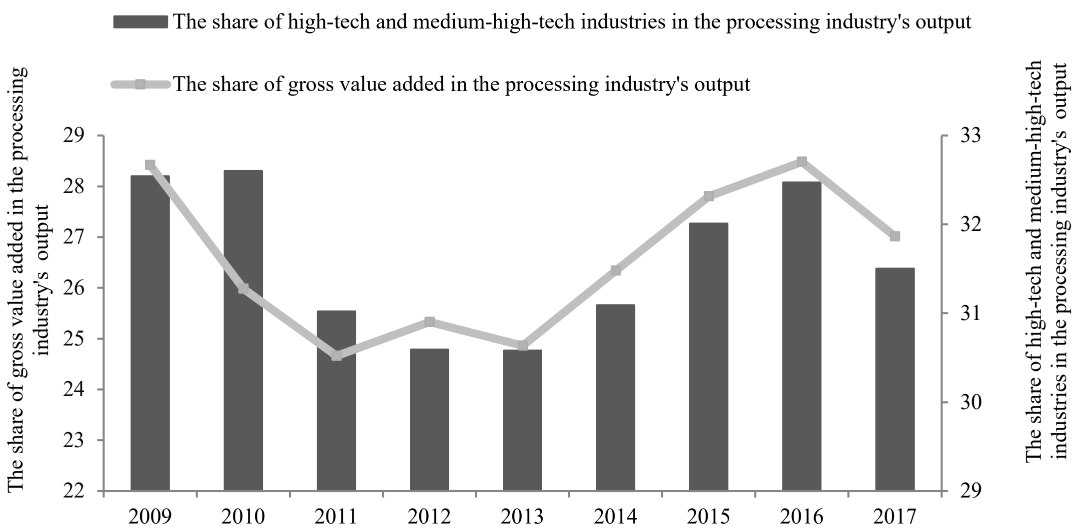


Fig. 1. Dynamics of structural indicators of the processing industry of Poland (%)
Source: elaborated by the authors based on Eurostat data.

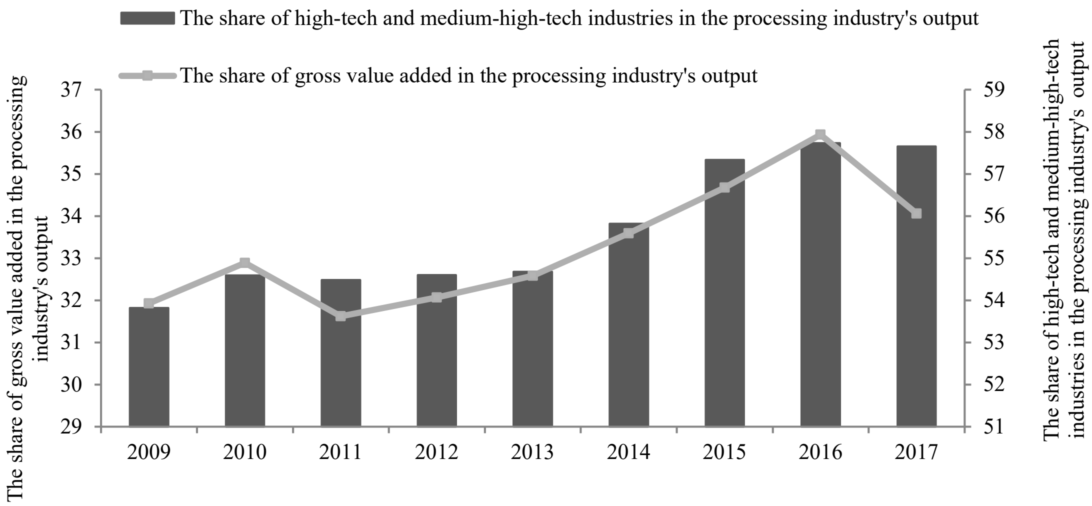
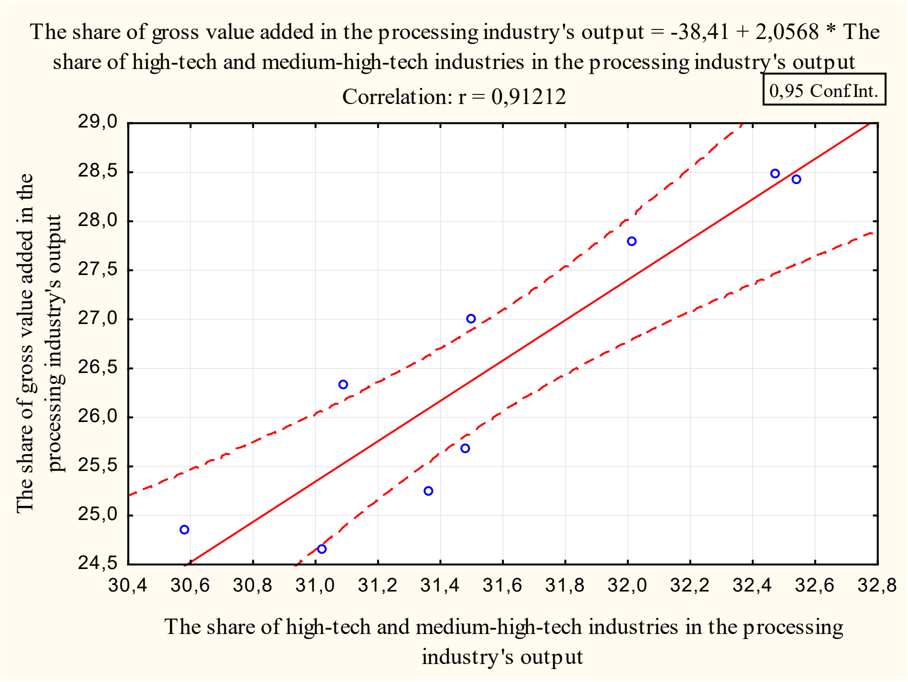


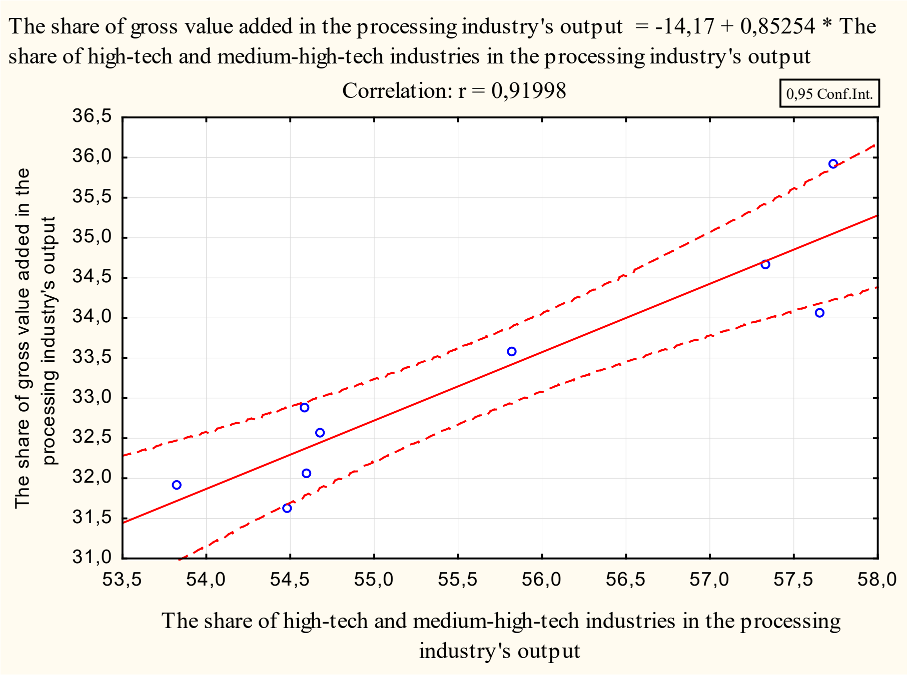
Fig. 2. Dynamics of structural indicators of the processing industry of Germany (%)
Source: elaborated by the authors based on Eurostat data.



Multiple R = 0.91212261; R^2= 0.83196765; Adjusted R^2= 0.80796303; Standard error of estimate: 0.654909995; F = 34.65865; df = 1.7; p = 0.000607; Intercept: -38.41398182; Std. Error: 11.02872; t(7) = -3.483; p = 0.0102

Fig. 3. Relationship between the share of high-tech and medium-high-tech industries in the processing industry's output and share of GVA in the processing industry's output in Poland

Source: elaborated by the authors based on Eurostat data.



Multiple R = 0.91998061; R^2= 0.84636433; Adjusted R^2= 0.82441638; Standard error of estimate: 0.599371375; F = 38.56234; df =1.7; p = 0.000441; Intercept: -14.16868929; Std. Error: 7.640436; t(7) = -1.854; p =0.1061

Fig. 4. Relationship between the share of high-tech and medium-high-tech industries in the processing industry's output and share of GVA in the processing industry's output in Germany

Source: elaborated by the authors based on Eurostat data.

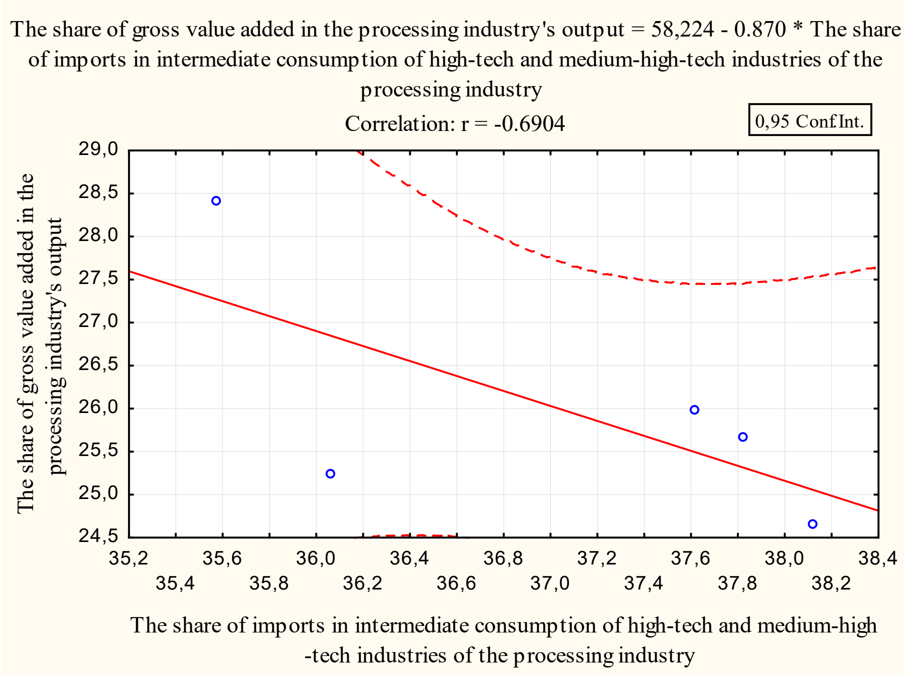
Tab. 3. Share of GVA in the processing industry's output and the share of imports in the intermediate consumption of the processing industry in Poland, the Czech Republic and Germany (%)

The group	Manufacturing	Code classification of economic activities ISIC Rev.4	Poland		Czech Republic		Germany	
			The share of gross value added in output	The share of imports in intermediate consumption	The share of gross value added in output	The share of imports in intermediate consumption	The share of gross value added in output	The share of imports in intermediate consumption
Medium-high and high technology	Computer, electronic and optical products	D26	18.57	46.74	18.94	53.13	47.07	35.89
	Chemicals and pharmaceutical products	D20T21	29.20	34.49	29.28	38.94	38.07	30.00
	Electrical equipment	D27	25.11	44.00	30.63	50.90	41.39	29.72
	Machinery and equipment, n.e.c.	D28	32.13	40.11	31.77	39.05	39.18	24.98
	Motor vehicles, trailers and semi-trailers	D29	20.95	34.73	19.43	47.95	32.35	24.83
	Other transport equipment	D30	30.40	49.04	36.38	38.86	34.21	35.45
	Total		**25.06**	**38.81**	**23.85**	**46.97**	**37.10**	**27.43**
Medium technology	Rubber and plastic products	D22	29.97	35.49	32.33	50.50	36.68	30.52
	Other non-metallic mineral products	D23	35.71	19.52	37.06	30.64	38.04	20.33
	Basic metals	D24	20.80	27.56	22.38	36.70	21.92	28.32
	Other manufacturing; repair and installation of machinery and equipment	D31T33	38.10	27.43	37.31	35.43	44.14	22.37
	Total		**32.40**	**28.53**	**32.12**	**40.09**	**34.43**	**26.30**
Low technology	Food products, beverages and tobacco	D10T12	24.41	15.32	26.17	24.95	25.16	21.13
	Textiles, wearing apparel, leather and related products	D13T15	36.58	33.57	33.66	46.29	32.92	29.01
	Wood and products of wood and cork	D16	29.35	15.24	27.78	20.10	28.36	17.87
	Paper products and printing	D17T18	31.08	25.75	28.48	36.28	33.31	23.39
	Coke and refined petroleum products	D19	14.37	53.3	5.27	77.86	10.61	55.77
	Fabricated metal products	D25	36.99	33.47	35.72	39.27	43.17	23.79
	Total		**27.33**	**25.99**	**28.44**	**37.38**	**29.86**	**27.39**
	Total processing industry		**27.81**	**30.82**	**26.60**	**43.37**	**34.79**	**27.22**

Source: elaborated by the authors based on OECD data.

- The shares of high-tech and the medium-high-tech industries in the processing industry's output and GVA should grow.

In some EU countries, high-tech industries are not sufficiently effective. These are, in particular, the Czech Republic, Hungary, Slovenia and Slovakia — countries with a high level of import dependence characteristic to the processing industry. In the Czech Republic, despite a high share of high-tech and medium-tech industries within the structure of the processing industry (56.30% in 2017), their share of GVA in output was only 26.82%. In this country, in-depth studies found a relatively high (43.37%) share of imports in intermediate consumption of the processing industry, including high-tech and medium-high-tech industries, which amounted to 46.97% in 2015 (this being the last year, for which the shares of imports in the intermediate consumption of processing industries of EU countries were available). In Poland, these indicators were, respectively, 30.82%



Multiple R: 0.69041263; R^2: 0.47666960; adjusted R^2: 0.30222614; Standard error of estimate: 1.203776159; Intercept: 58.224202892; Std. Error: 19.50324; t(3) = 2.9854; p = 0.196895; p < 0.0583; df = 1.3

Fig. 5. Relationship between share of GVA in the processing industry's output and the share of imports in the intermediate consumption of high-tech and medium-high-tech industries in Poland

Source: elaborated by the authors based on OECD data.

and 38.81%, and in Germany, 27.22% and 27.43% (Table 3)[1].

According to Table 3, the smaller is the share of imports in the intermediate consumption (primarily of high-tech and medium-high-tech industries), the higher is share of GVA in the processing industry's output.

Results of the correlation and regression analysis confirmed the presence of a stochastic connection and inverse relationship between the change in share of GVA in the processing industry's output and the share of high-tech and medium-high-tech industries in all three studied countries. However, the degree of dependency between these indicators varied from country to country. This relationship was very high in the Czech Republic (the correlation coefficient was -0.92), high in Poland (-0.69), and low in Germany (-0.17) (Figs. 5–7). Determination coefficients show that the dependence of share of GVA in the processing industry's output on the share of imports in the intermediate consumption of high-tech and medium-high-tech industries amounts to 84.04% in the Czech Republic, 47.67% in Poland, and as little as 2.94% in Germany.

Thus, the results of the analysis confirmed the second hypothesis: the lower is the share of imports in the intermediate consumption of high-tech and medium-high-tech industries, the higher is share of GVA in the processing industry's output.

Consequently, the optimised structure of the intermediate consumption of the processing industry in favour of the domestic components of high-tech and medium-high-tech industries increases the efficiency of the processing industry.

The functional relationship between share of GVA in the processing industry's output and the structure (in terms of domestic and imported components) of the intermediate consumption is represented by the optimisation model:

$$\frac{q}{p}=\frac{q_1+q_2+\ldots+q_{16}}{q_1+c_1\left(\frac{d_1}{c_1}+\frac{i_1}{c_1}\right)+q_2+c_2\left(\frac{d_2}{c_2}+\frac{i_2}{c_2}\right)+\ldots+q_{16}+c_{16}\left(\frac{d_{16}}{c_{16}}+\frac{i_{16}}{c_{16}}\right)}\rightarrow opt, \quad (3)$$

[1] The names, codes and groups of industries within the processing industry listed in Table 3 correspond to the ISIC Rev.4 economic activity classification system. This decision was made because the fullest body of information, which was required to calculate the share of imports in intermediate consumption of industries within the processing industry, was available from OECD (2019), where it was given according to the named system. The manufacturability groups were formed according to the levels of the technological intensity of ISIC Rev.4 UNIDO (2019). It should also be noted that Furniture production (Division 31) was classified as Medium rather than Low technology, as required by UNIDO (2019). This decision was made because the OECD (2019) information concerning the imports of intermediate consumption of Furniture (Division 31) was presented in D31T33: Other manufacturing; repair and installation of machinery and equipment.

where:

q – the gross value added of the processing industry;

p – the output of the processing industry;

$q_1, q_2, \dots, q_{16}$ – the gross value added of 16 industries of the processing industry;

$c_1, c_2, \dots, c_{16}$ – intermediate consumption of the 16 industries;

$\frac{d_1}{c_1}, \frac{d_2}{c_2}, \dots, \frac{d_{16}}{c_{16}}$ – the shares of domestic components in the intermediate consumption of each of the 16 industries;

$\frac{i_1}{c_1}, \frac{i_2}{c_2}, \dots, \frac{i_{16}}{c_{16}}$ – the shares of imported components in the intermediate consumption of each of the 16 industries.

The target function of the optimisation was to increase the actual share of GVA in the processing industry's output to the desired level.

The following limitations and criteria were defined for the optimisation function (2):

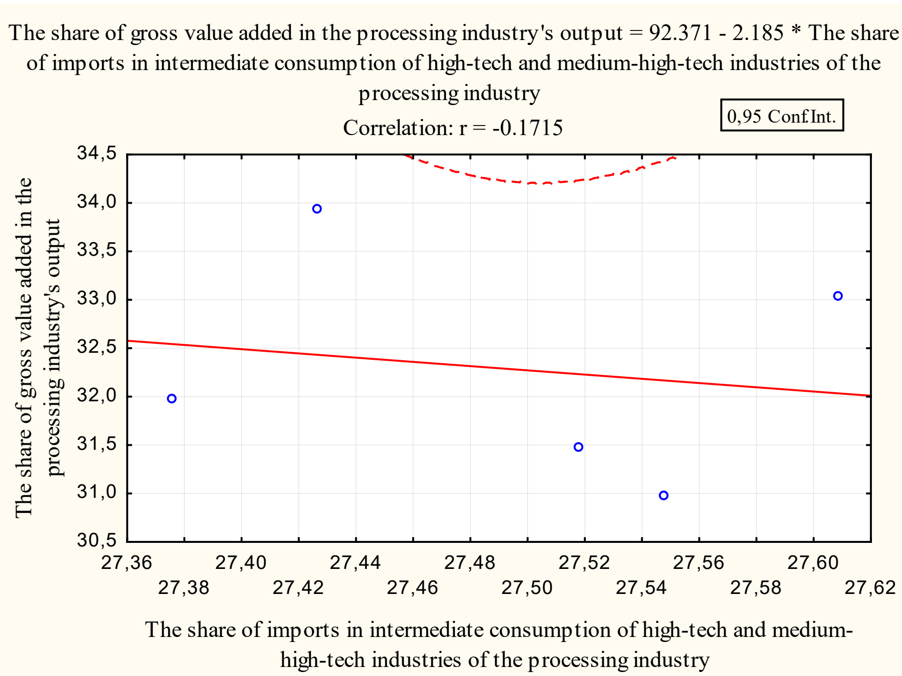
1. The total sum of the shares of domestic and imported components of the intermediate consumption for each of the 16 industries is 1:

$$\left(\frac{d_1}{c_1}+\frac{i_1}{c_1}\right)=1,\ \left(\frac{d_2}{c_2}+\frac{i_2}{c_2}\right)=1,\dots,\ \left(\frac{d_{16}}{c_{16}}+\frac{i_{16}}{c_{16}}\right)=1 \qquad (4)$$

- The volumes of GVA and the output of the processing industry are equal to the sums of the GVAs and outputs of the 16 industries.
- The share of domestic components in the intermediate consumption of high-tech and medium-high-tech industries is inclined to grow, while the share of imported components — to decline.
- Shares of GVA in output for each of high-tech and medium-high-tech industries should increase.

2. Results

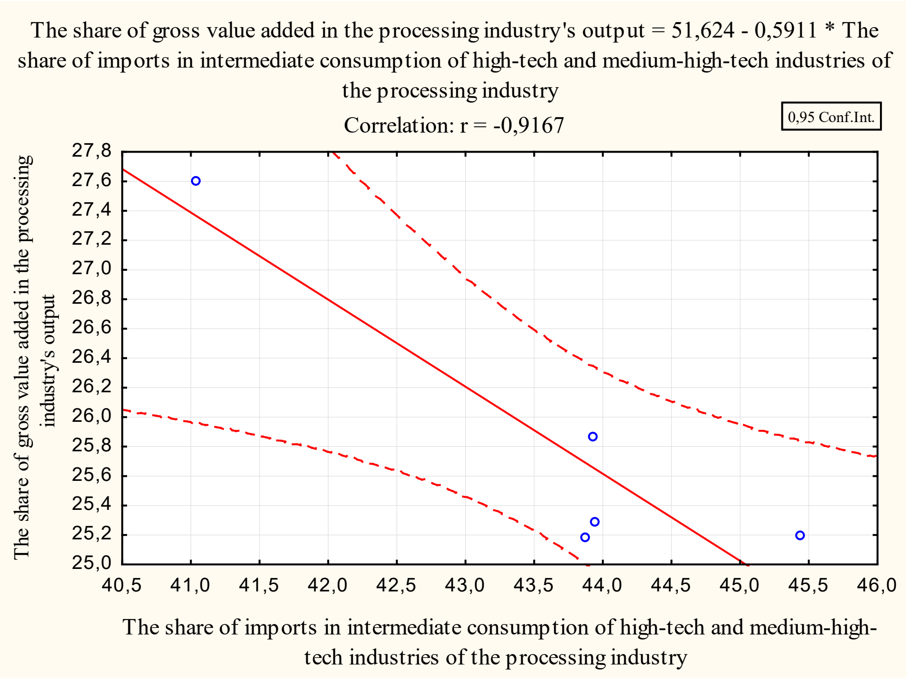
The optimisation model (1) was solved using the linear programming method. The input data for calculations were the values of structural indices of the processing industry in Poland. The target function was to achieve 34.06% (Germany's value) in terms of share of GVA in the processing industry's output in Poland. As a result of the calculations, the optimised structures of output and GVA for the processing industry in Poland were obtained (Table 4).



Multiple R: 0.17154493; R^2: 0.02942766; adjusted R^2: -0.29409645; Standard error of estimate: 1.360032654; Intercept: 92.370829663; Std. Error: 199.2361; F = 0.0909597; t(3) = 0.46363; p = 0.782658; p < 0.6745; df = 1,3

Fig. 6. Relationship between share of GVA in the processing industry's output and the share of imports in the intermediate consumption of high-tech and medium-high-tech industries in Germany

Source: elaborated by the authors based on OECD data.



Multiple R: 0.91671400; R^2:0,84036455; adjusted R^2: 0.78715273; Standard error of estimate: 0.475927705; Intercept: 51.624065020; Std. Error: 6.494768; F = 15.79282; p = 0.028490; p < 0.0042; t(3) = 7.9486; df = 1.3

Fig. 7. Relationship between share of GVA in the processing industry's output and the share of imports in the intermediate consumption of high-tech and medium-high-tech industries in the Czech Republic

Source: elaborated by the authors based on OECD data.

Tab. 4. Optimised structures of GVA and output for the processing industry in Poland (%)

The group	The manufacturing	Classification code of economic activities NACE Rev.2	The gross value added structure	The output structure	The share of gross value added in output
The high-tech	Manufacture of basic pharmaceutical products and pharmaceuticals	C21	2.22	1.54	49.01
	Manufacture of computers, electronic and optical products	C26	4.02	3.42	40.00
	Total		**6.23**	**4.96**	**42.80**
The medium-high-tech	Manufacture of chemicals and chemical products	C20	6.13	5.50	37.96
	Production of electric equipment	C27	5.83	4.97	39.98
	Manufacture of machinery and equipment not elsewhere classified	C28	4.91	4.51	37.05
	Production of motor vehicles, trailers and semitrailers	C29	13.27	13.74	32.89
	Manufacture of other transport equipment	C30	2.43	2.52	32.87
	Total		**32.57**	**31.24**	**35.51**
The moderately-low-tech	Production of coke and coke products of oil refining	C19	2.99	5.29	19.25
	Manufacture of rubber and plastic products	C22	7.43	7.24	34.96
	Manufacture of other non-metallic mineral products	C23	4.64	4.37	36.17
	Metallurgical production	C24	2.37	4.22	19.13
	Manufacture of fabricated metal products, except machinery and equipment	C25	8.86	7.40	40.78
	Repair and installation of machinery and equipment	C33	4.77	3.00	54.21
	Total		**31.07**	**31.52**	**36.46**

The low-tech	Manufacture of food products; beverages and tobacco products	C10-12	15.08	19.01	27.01
	Manufacture of textiles, wearing apparel, leather and related products	C13-15	2.31	2.20	35.78
	Manufacture of wood, paper, printing and reproduction	C16-18	7.64	7.20	36.12
	Manufacture of furniture; other manufacturing	C31-32	5.11	3.87	44.97
	Total		**30.13**	**32.28**	**31.79**
Total processing industry			**100.00**	**100.00**	**34.06**

Source: elaborated by the authors based on Eurostat data.

According to the results, the processing industry in Poland will be able to reach the German level of efficiency (the share of GVA in output at the level of 34.06%) on the condition that the share of high-tech and medium-high-tech industries in the output structure will increase by 4.69 pp. At the same time, share of GVA of high-tech and medium-high-tech industries in the processing industry's GVA should increase by 11.02 pp in Poland.

The optimisation model (2) was solved using the linear programming method. The initial data for the calculations were the values of structural indicators of the Czech processing industry. The target function was to achieve 34.79% for share of GVA in the processing industry's output in the Czech Republic (which is the indicator for Germany in 2015). According to the simulation results, an optimised structure of the intermediate consumption of the Czech processing industry was constructed (Table 5).

Thus, ratios were determined between the share of domestic and imported components of the intermediate consumption for all 16 industries, at which the level of efficiency of the Czech processing industry would reach the level of Germany in 2015 (share of GVA in output amounting to 34.79%). Such an efficiency indicator can be achieved under the condition that the import share in the intermediate consumption of high-tech and medium-high industries of the Czech processing industry is decreased by 18.49 pp.

Conclusions

The study into the industrial sector of the EU economy, in particular Poland and Germany, suggested a relationship between the efficiency of the processing industry and its structure. The results of the correlation and regression analysis proved the adequacy of the hypothesis stating that the higher was the share of high-tech and medium-high-tech industries of the processing industry's output, the higher was share of GVA in output of these types of industrial activity. This led to the conclusion that the optimisation of the processing industry's output structure was a way to increase the efficiency of this industry. Based on this statement, an optimisation model was constructed, in which the target function was to increase share of GVA in the processing industry's output to the desired level, and the main optimisation criterion was increasing the share of high-tech and medium-high-tech industries in the output structure.

Further research found that the high-tech processing industry was not always effective. This particularly applies to such countries as the Czech Republic, Hungary, Slovenia and Slovakia, i.e. countries with a high level of import dependence in the processing industry. The results of the correlation and regression analysis, conducted on the example of the Czech Republic, proved the adequacy of the second hypothesis stating that the lower was the share of imports in the intermediate consumption of high-tech and medium-tech industries, the higher was the share of GVA in the processing industry's output. Hence, another way for increasing the efficiency of the processing industry was defined as the optimisation of the structure pertaining to the intermediate consumption of high-tech and medium-high-tech industries. According to this hypothesis, an optimisation model was developed, which allowed determining ratios between domestic and imported components in the structure of the intermediate consumption of the industries within the processing industry, that would allow achieving the desired level of efficiency.

The developed economic and mathematical models were solved using the method of linear programming. In both models, the share of GVA in the German processing industry's output as a benchmark was chosen as the target function. The first model was tested on the example of Poland, in particular, the

Tab. 5. Optimised structure (in terms of domestic and imported components) of the intermediate consumption of the processing industry in the Czech Republic (%)

The group	The manufacturing	Code classification of economic activities ISIC Rev.4	Actual data (2015)			Optimised data		
			The share of gross value added in output	The share of domestic component in intermediate consumption	The share of imported component in intermediate consumption	The share of gross value added in output	The share of domestic component in intermediate consumption	The share of imported component in intermediate consumption
Medium-high and high technology	Computer, electronic and optical products	D26	18.94	46.87	53.13	20.12	64.64	35.36
	Chemicals and pharmaceutical products	D20T21	29.28	61.06	38.94	32.21	65.92	34.08
	Electrical equipment	D27	30.63	49.10	50.90	31.21	65.44	34.56
	Machinery and equipment, n.e.c.	D28	31.77	60.95	39.05	33.21	66.60	33.40
	Motor vehicles, trailers and semi-trailers	D29	19.43	52.05	47.95	22.21	77.56	22.44
	Other transport equipment	D30	36.38	61.14	38.86	38.21	64.17	35.83
	Total		**23.85**	**53.03**	**46.97**	**26.06**	**71.52**	**28.48**
The moderately-low-tech	Rubber and plastic products	D22	5.27	22.14	77.86	7.39	23.79	76.21
	Other non-metallic mineral products	D23	32.33	49.50	50.50	35.51	64.35	35.65
	Basic metals	D24	37.06	69.36	30.64	52.38	71.80	28.20
	Other manufacturing; repair and installation of machinery and equipment	D31T33	22.38	63.30	36.70	42.07	64.50	35.50
	Total		**35.72**	**60.73**	**39.27**	**37.41**	**76.40**	**23.60**
The low-tech	Food products, beverages and tobacco	D10T12	29.95	54.85	45.15	36.84	64.14	35.86
	Textiles, wearing apparel, leather and related products	D13T15	26.17	75.05	24.95	42.71	77.67	22.33
	Wood and products of wood and cork	D16	33.66	53.71	46.29	36.55	56.04	43.96
	Paper products and printing	D17T18	27.78	79.90	20.10	29.89	80.44	19.56
	Coke and refined petroleum products	D19	28.48	63.72	36.28	31.64	64.37	35.63
	Fabricated metal products	D25	37.31	64.57	35.43	38.20	67.43	32.57
	Total		**30.11**	**69.83**	**30.17**	**37.85**	**71.15**	**28.85**
Total processing industry			**26.60**	**56.63**	**43.37**	**34.79**	**74.97**	**25.03**

Source: elaborated by the authors based on OECD data.

optimised structures of the output and GVA of the processing industry of this country were built according to the criterion of increasing the technological level. The second model was tested on the example of the Czech Republic, in particular, the optimised structure of the intermediate consumption of the industries was built according to the criterion of reducing import dependence.

Further research in this direction will focus on modelling the impact of other factors on the level of processing industry's efficiency, in particular, the specificities of the high-tech industries from the perspective of the creation of value-added chains.

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Robotic Process Automation — a driver of digital transformation?

Julia Siderska

ABSTRACT

The paper introduces Robotic Process Automation (RPA), which is an emerging and cutting-edge conception of business processes automation, based on the notion of software robots or artificial intelligence workers. The paper is conceptual as it discusses the fundamentals behind this idea, synthesises the knowledge of technology, and presents it in a new context. It is based on the author's considerations and the literature review, which contributes to the insight into the basic understanding of RPA technology as well as systematises and clarifies RPA definitions, identifies market trends, formulates a set of predictions for further development of this technology, and highlights directions for future inquiry. Additionally, logical arguments are proposed for considering RPA as a technology that enables and advances digital transformation. Moreover, criteria are indicated for business processes suitable for RPA. Nowadays, the robotisation of business processes as innovative technology is more often practically implemented than it is investigated by research. Published papers outline real examples of implemented cases of RPA technology in organisations that mainly represent service industries. These case studies allow identifying possible advantages and risks derived from RPA implementation. Recent studies also report benefits of the RPA application in terms of productivity, costs, service quality, and error reduction. Some authors propose the criteria for selecting processes suitable for automation and robotisation. This paper constitutes a foundation for new research aimed at filling knowledge gaps in this area. Responding to the call by van der Aalst, academic discourse on RPA must be initiated.

KEY WORDS

Robotic Process Automation, RPA, digital transformation, software robots, digital technologies, artificial intelligence

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Introduction

With digital technologies shaping competition in many industries, predicting the future of potentially disruptive technologies becomes an essential task of business leaders concerned with the survival and success of their organisations (Krotov, 2019). Several years have seen the rapid growth of the importance of digital technologies in achieving business goals of organisations. The use of advanced digital technologies transforms business models of organisations,

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their products, processes and organisational structures. Such changes are called digital transformation, and they revolutionise both individual enterprises as well as whole industries.

Until now, the concept of digital transformation was primarily associated with production processes as physical robots were supporting humans in manufacturing tasks. At the beginning of the digital transformation era, all attempts were mainly directed towards providing the highest quality of customer service. Currently, increasingly more attention is devoted to the digitisation of operational and business processes, and the concept of digitisation itself also covers service enterprises, including primarily such industries as finance, banking, insurance, marketing, accounting, public administration, logistics, etc.

Rapidly changing market demands, and the dynamic development of information technologies significantly contribute to the evolution of modern management concepts using IT tools. While the robotisation of production processes (the manufacturing sphere of an organisation) emerged in the 1950s, the robotisation of business processes (the sphere of management) is still at the beginning of the expansion and seems to have a potential for development in companies. In this context and the light of the available literature on the subject, such robotisation should be widely understood as the automation of business processes through the extensive use of "robots", i.e. software that replaces people in certain activities. RPA is used to automate data-intensive and repetitive tasks for improved process efficiency. Robotic Process Automation literally may suggest physical robots occupying office space, performing human tasks, and being involved in business processes. However, RPA is essentially a software-based solution, and the software "robot" is expected to perform activities previously undertaken by people (Das, 2019). Detailed considerations specifying the meaning of this concept are presented in the next chapter.

The value of the RPA market has been increasing for several years, and the analytics anticipate further development of this sector. To illustrate this intensifying adoption of RPA solutions in companies, Forrester predicted that by 2021, more than four million robots would be implemented for office tasks. Moreover, according to these forecasts, the RPA market would reach USD 2.9 billion by 2021, from USD 250 million in 2016 (Le Clair, 2018). Gartner considered RPA as "the fastest-growing segment of the global enterprise software market" and anticipated that the global market for RPA services would hit an estimated EUR 7 billion in 2020 (Gartner, 2017). It is worth emphasising that it is currently the most rapidly developing segment of the global software market. According to Information Services Group (2018), 54% of European companies plan to automate at least ten processes via RPA within 2020. The RPA industry is growing rapidly, driven by digital business demands as organisations look for "straight-through" processing.

Aiming to meet the set goals, the paper is structured as follows. The introduction is followed by a brief background on RPA and the literature review, which systematises RPA definitions and indicates the main possibilities that open up with the application of such solutions in service companies. The third part of the paper identifies the main characteristics and advantages for enterprises considering the implementation of automated software robots. In addition, the author offers several arguments for considering RPA as an emerging and cutting-edge technology that enables digital transformation. Next, criteria are formulated for processes that are suitable for RPA. In the third chapter, the author indicates the proposals of integrating RPA with other disruptive technologies. The proposals are followed by future-oriented predictions for further development of RPA tools. The last part of the paper offers conclusions and highlights directions for prospective inquiry.

1. Literature review

Insufficient literature is available on Robotic Process Automation as a niche and nascent field. Although RPA is an emerging and promising technology, scientific research is almost absent. The academic research mainly lacks a theoretical and synoptic analysis of such an approach. Some authors have documented its features and benefits in whitepapers and case studies. However, there is a need for a comprehensive assessment of this concept, indicating roadmaps for effective deployment towards organisational value creation (Das, 2019).

The literature analysis was conducted by the author aiming to provide an insight into the fundamental understanding of RPA and to systematise RPA definitions offered in different scientific papers. Researchers represent three main approaches to understanding and defining the essence of this concept. The literature considers it as emerging technology, a software tool, or a process automation approach. However, all proposed definitions emphasise the reduction of the burden of repetitive, simple tasks and their automation as the main aim of those tools. They enable employees to be involved in more complicated tasks that require creativity and which can bring more value to an organisation. The technology is mostly driven by simple rules and business logic. It interacts with multiple information systems through existing graphic user interfaces. Its functionalities comprise the automation of repeatable and rule-based activities (Greyer-Klingeberg et al., 2018). Fig. 1 presents the key areas for the application of automated software robots.

Santiago and Rodriguez (2019) determined the concept of RPA as an "automation technology based on software tools that could imitate human behaviour for repetitive and non-value added tasks, such as tipping, copying, pasting, extracting, merging and moving data from one system to another". According to Gartner (2017), "RPA tools perform [if, then, else] statements on structured data, typically using a combination of user interface interactions, or by connecting to APIs to drive client servers, mainframes or HTML code. An RPA tool operates by mapping a process in the RPA tool language for the software robot to follow, with runtime allocated to execute the script by a control dashboard". Based on Slaby (2012), RPA is the technological imitation of a human worker aimed at fast and cost-efficient automation of structured tasks. Some authors also pointed to several RPA disadvantages that companies must consider when adopting RPA to automate processes. This technology is only suited for rule-based processes because it is executed by a robot without cognitive skills. Moreover, processes containing many exceptions should be handled by workers (Santos et al., 2019). It should also be emphasised that such processes must be firstly identified, standardised and optimised. According to studies by the IEEE Advisory Group (IEEE SA, 2017), RPA technology is "preconfigured software instance that uses business rules and predefined activity choreography to complete the autonomous execution of a combination of processes, activities, transactions and tasks in one or more unrelated software systems

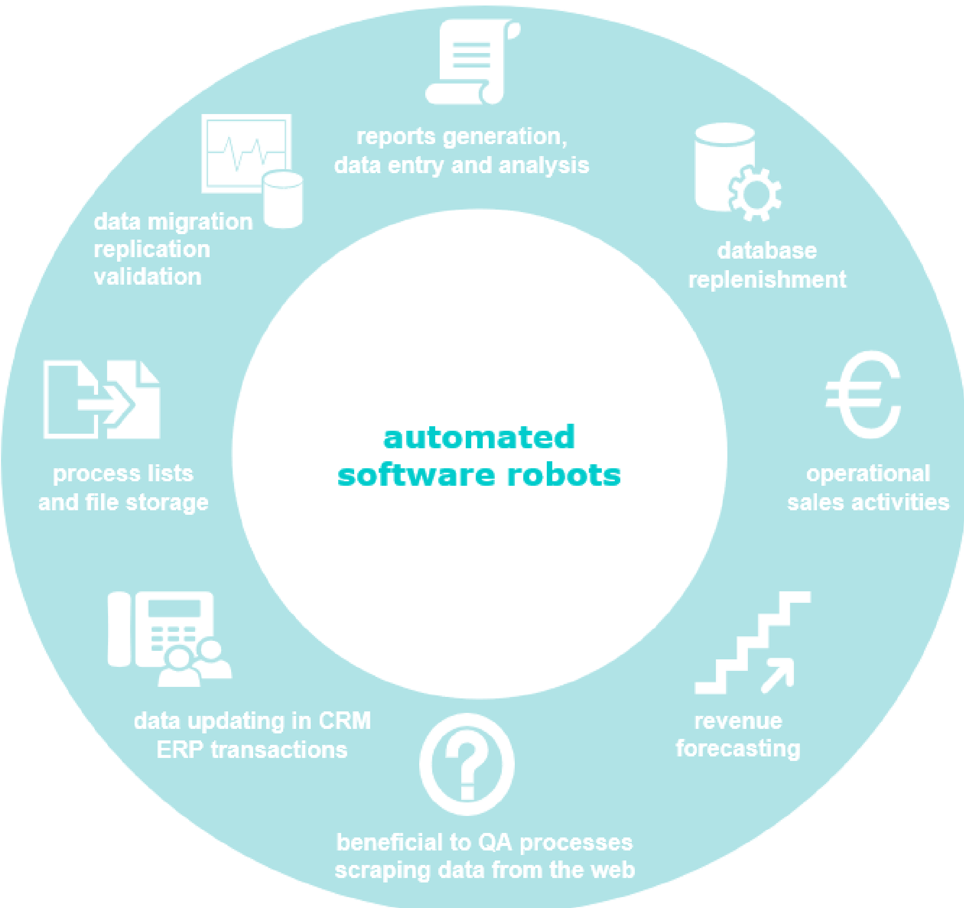

Fig. 1. Leading applications of automated software robots.

to deliver a result or service with human exception management".

In the literature on the subject, the RPA conception is also identified as a process automation approach. According to Quinn and Strauss (2018), RPA is "a fast-emerging process automation approach that uses software robots to replicate human tasks. After recording a process workflow, a virtual bot mimics the actions performed by humans in the application's graphical user interface and automate their execution". A similar definition was proposed by Lacity and Willcocks, stating that "RPA can automate rules-based processes that involve routine tasks, structured data and deterministic outcomes". Most applications of RPA were created for automating tasks of service business processes (Fig. 1). RPA is commonly perceived "as a productivity and effectiveness tool as it reduces errors, increases security and helps lessen human mistake" (Dialani, 2019).

Automated software robots are increasingly adopted in many areas, such as human resources (Hallikainen et al., 2018), IT (Khramov, 2018), finance (Lacity et al., 2017), insurance (Lacity & Willcocks, 2017), telecommunication (Lacity et al., 2015), education (Herbert, 2016), banking (Willcocks et al., 2017), legal services (Holder et al., 2016), real-estate management and logistics (Jurczuk, 2019).

According to some authors, RPA should be considered from two perspectives, namely, the future of an organisation and changes in the labour market. The first approach should be understood as the occurrence of natural processes resulting from technological development, the rapid pace of knowledge growth, and their impact on the economic environment of an organisation. The second approach may be defined as a reconfiguration of the current and the formation of new, previously unknown workplaces in the labour market (Śliż, 2019).

2. RPA characteristics of and Its influence on digital transformation

Robotic Process Automation should be considered as one of the digital transformation technologies supporting companies in robotising repeatable and routine tasks. Just like other advanced solutions, RPA enables higher efficiency. By programming autonomous software robots to replicate basic administrative processes, it merges software, artificial intelligence, and machine learning capabilities to automate manual tasks that are normally operated by humans (Kudlak, 2019).

Software robots developed with the use of RPA tool allow solving plenty of business problems. Next, the main characteristics and advantages are listed for an enterprise after implementing such solutions (Sobczak, 2019; Anagoste, 2017; the author):

- the ability for employees supported by robots to handle more processes, work more efficiently and commit fewer errors in analysing data;
- the increased repeatability, reproducibility, and quality of most office processes;
- the robotisation of processes that relieves employees from the most routine, repetitive tasks, entrusting them with more demanding duties; the raised standardisation of repetitive tasks to a higher level;
- more time for employees to engage in creative work and problem-solving; business processes made up to ten times faster;
- quick results brought by RPA, possible to be implemented in organisations with a technological debt;
- checks and takes performed in consideration validation points according to a predefined set of rules;
- flawless work with multiple systems, interconnecting many computer applications and systems (e.g. PDF, MS Excel, ERP system, PowerPoint etc.);
- a case provided for the introduction of analytics;
- a possibility to personalise a solution for an individual user, extract specific information from e-mails and respond with security procedures and data confidentiality;
- the reliability of software robots as they constantly adhere to the predefined workflow, which increases process reliability and compliance;
- the robotisation of business processes can be implemented in many industries (nowadays, it is mainly used in accounting and finance, banking, insurance, telecommunications and logistics);
- reduced operational costs.

The fundamental issue for the company should be the appropriate identification of processes to be automated using RPA technology. A proper selection of processes for robotisation is critical as it differs at the Proof-of-Concept stage and during the implementation in an organisation. The analyses allowed to indicate a set of ideal processes, considering their frequency and complexity. The study by Capgemini

Consulting assumed that highly frequent processes with low complexity were typically automated using some of the traditional business process automation methods, while processes that were more complex and more frequent were ideal for RPA automation. Also, processes with low frequency and high complexity should not be automated using RPA (Fig. 2).

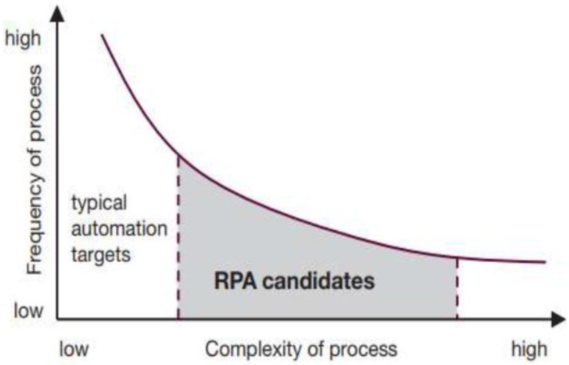

Fig. 2. RPA candidates by frequency and complexity of a process
Source: (Jovanovic et al., 2018).

According to Fung (2014), the typical criteria for processes suitable for RPA are:

- low cognitive requirements (it is hardly possible for complex processes with many complicated tasks to be handled by RPA);
- no requirement for the access to multiple systems as RPA is applied on top of existing applications;
- relatively frequently performed processes and tasks are good candidates for RPA implementation;
- processes with a high probability of human error and limited exceptions should be selected first for RPA.

Over the last few years, digital transformation was mostly influenced by such technologies as cloud, edge computing, IoT, and AR (Gudanowska, 2017; Siderska & Jadaan, 2018; Ślusarczyk, 2018; Ejdys et al., 2019; Krykavskyy, 2019; Nosalska & Mazurek, 2019; Gudanowska & Kononiuk, 2020; Halicka, 2020). However, analytics emphasise that up to 2020, a set of such technologies will be supplemented with others that will significantly affect the digital revolution, namely, 5G, AI, advanced analytics, Machine Learning, blockchain (Hofbauer & Sangl, 2019), conversational AI, XaaS, connected vehicles, autonomous drones, and smart cities (Szpilko, 2020; Forbes, 2019; Winkowska et al., 2019).

In the author's opinion, RPA should also be considered an emerging and cutting-edge technology that enables digital transformation. The fourth industrial revolution is powered by the rise of such digital technologies as rapidly transforming processes and human–technology relationships. The technology substitutes manual labour, no longer playing a supporting role. Taking up the challenges of the digital revolution to digitise operational processes and automate some routine tasks, a growing number of companies is implementing disruptive technologies and modern IT tools, including principally Robotic Process Automation (RPA). Such solutions are user-configurable, do not require code writing and use non-invasive techniques (operating on HTML pages, "screen scraping" or scripts that enable work in many different environments, e.g. ERP, CRM, workflow, or email programs). As a result, RPA technology should be considered one of the enablers of Industry 4.0 and digital transformation, as it supports business processes transformation, product development, and new emerging business models. It also allows to achieve better operational efficiency and reduce significantly operational costs.

In the Age of Digital Transformation, artificial intelligence and machine learning enable robots to learn new skills as well as extend the scope of their work beyond rules-based-action to conclusions and decision-making tasks. To help humans, software robots should not only undertake the basic work but also have to be able to act intelligently (Kirkwood, 2019). Robotic Process Automation technologies are becoming compulsory as a part of business operations in an organisation. It should be noted that RPA technologies will undertake repetitive tasks and even get involved in risky processes of human life (Madakan et al., 2019). Due to increased versatility and disruptive potential to transform business processes, intelligent automation will be the next milestone for worth-while investments. The joint use of RPA and complementary technologies (artificial intelligence, business process management, OCR, process orchestration, machine learning, or natural language processing) enables the automation of increasingly more complex processes.

3. Future RPA opportunities

RPA supported by modern technologies will become more comprehensive and all-embracing. Together with artificial intelligence, robots will come up with different solutions to further ease the workflow of organisations. Bots, combined with intelligent technologies, accelerate the rate of the learning process. Software, which is integrated with such technologies as Machine Learning, artificial (cognitive) intelligence, Natural Language Processing and data analytics, can analyse and process data available in real-time. Furthermore, it can accurately predict the time left to complete a task or a milestone while still executing the process or even beforehand. The industries will be assisted by RPA to streamline business processes all the time and optimise operational efficiency.

Table 1 presents the proposals found in the literature regarding the integration of RPA with other cutting-edge technologies and areas.

RPA is often discussed and described in the literature as a gateway technology to artificial intelligence. Dialani (2019) found that Robotic Process Automation as "the subset of AI that empowers IT groups to configure software 'robots' to capture data and perform routine tasks, is picking up traction as an alluring spot to start with outcomes centred AI implementation. RPA is getting one of the most exciting opportunities in the AI space and will keep on sparkling in 2020". Future trends suggest that there will be a collaboration between bots and humans in many areas (Seibt & Vestergaard, 2018). As a result, more jobs will be created by enhancing the nature of jobs, and there will be a need for RPA and process experts to augment user interfaces and solve business problems.

Tab. 1. Integration of RPA and other technologies

Technology	References
Integration with machine learning/ artificial intelligence/ cognitive intelligence/ Natural Language Processing	• Anagnoste (2017), • Anagnoste (2018), • val der Aalst et al. (2018), • Sobczak (2019), • Madakam et al. (2019), • Dialani (2019), • Kudlak (2019)
Integration with big data/ analytics/data analysis	• Anagnoste (2017), • Tian (2018), • Ivancic et al. (2019)
Integration with process mining	• val der Aalst et al. (2018), • Tornbohm and Dunie (2017), • Ivancic et al. (2019), • Geyer-Klingeberg et al. (2018)
Integration with BPM/ BPMS	• Mendling et al. (2018), • Das (2019), • Ivancic et al. (2019), • Santos, Pereira (2019), • Śliż (2019), • Jovanović et al. (2018)

The constant advancement of RPA and AI is hard to keep up with; however, following these global trends can provide companies with competitive advantages and domination in the market (Kot & Leszczyński, 2019). It is worth-while stressing that the comprehensive potential contributed by RPA to organisations across all industries should encourage their development and adaptation of a digital transformation strategy.

According to Forrester, most organisations have already automated at least 20% of service desk-tasks, and more than a million knowledge-worker jobs will be replaced by software robotics, RPA, virtual agents and chatbots and ML-based decision management (Forrester, 2019). However, this does not mean that posts will be freed, and workers will lose their jobs. Jurczuk claims that the current perception of the role of human resources must be reformulated and new roles in business processes must be indicated. The use of opportunities offered by new technologies should be the role of entrepreneurs and the process management approach (Jurczuk, 2019). The nature of performed tasks will change and, therefore, completely different employee competencies will be prioritised, including advanced digital competences. As the rate of RPA maturity and technology advancement will continue to accelerate in the near future, organisations will need to standardise and scale their automation. Moreover, they will have to address business challenges with a hybrid human/software workforce, using software robots to automate daily processes and freeing humans for more creative, strategic tasks.

Future-oriented predictions for further development of RPA tools were considered by Kirkwood, chief of UiPath — the global leader in the development of RPA platforms and the first vendor of scale to bring together process mining and Robotic Process Automation (Kirkwood, 2019):

- The global economic downturn will encourage the adoption of automation. As businesses face the realities of working in an economic downturn, they should adapt their business models with automation, which will enable them to scale up robots rather than scale down human employees;
- RPA is going to claim its place as a central platform for other enterprise automation tools. This is the front end of an even longer-term trend, as RPA becomes more accessible and extensible;
- More organisations will combine and reuse robots. In 2020, organisations will learn how to

better standardise robots and apply them across use-cases and departments, and eventually across companies and industries;
- Students entering the workforce will drive automation deployment. So far, human employees have been stuck having to connect and integrate increasingly outdated technology systems via repetitive, manual work. As new employees get more efficient and effective, the now vivid benefits of RPA will outweigh any remaining hesitancy, compelling organisation to change;
- The abilities of machine intelligence are continuing to grow. Tasks that we once thought uniquely human are quickly becoming doable by software. The growth of AI will remain exponential, RPA will become a topic discussed on the world stage;
- The impact of automation is proving to be societal in scope. In 2020, extra-governmental organisations such as the United Nations and the World Economic Forum will discuss RPA in the context of jobs, wages, and global economics. Individual countries will also become increasingly interested in what effect automation will have on their societies.

Robotic Process Automation should be considered a bridge between manual processes and full automation. As one of the core elements of Industry 4.0, it is the next step in the transformation attempts of companies. Although RPA software can be implemented in all industries, the biggest adopters are banks, insurance companies, telecommunication and utility companies. These organisations have traditionally had many legacy systems; therefore, they choose RPA solutions to ensure integration functionality. By using this technology, organisations can quickly accelerate their digital transformation initiatives while unlocking the value associated with past technology investments.

Nowadays, software robots can be more efficiently standardised, and this warrants their application across a wider range of use cases, departments, whole companies, and even industry sectors. By combining bots into reusable and repeatable elements, both their applicability and their power are enlarged to a considerable extent. Because of its increased versatility and disruptive potential to transform business processes, intelligent automation will be the next milestone for worth-while investments. The automation of increasingly more complex processes is enabled by the joint use of RPA and complementary technologies, such as artificial intelligence, business process management, optical character recognition, process orchestration, machine learning, and natural language processing.

Gartner considered cognitive automation a strategic trend and labelled it "hyperautomation". The expected benefits include increased capacity of robots to master unstructured data, to engage in intricate decision-making processes that consider a wider range of variables, and to learn from experience. As a consequence, the performance of a wide spectrum of business processes will be significantly upgraded. It is also possible to imply that RPA will be combined with Artificial Intelligence (RPAAI). Such an approach constitutes the concept of cognitive automation, combining AI with the automation of business processes. Sobczak believed that the use of the term "Augmented Intelligence" (AUI) was more justified, in the sense of enhanced or augmented intelligence. From the technological point of view, artificial intelligence and augmented intelligence use the same tools (e.g., Machine Learning/Deep Learning) but the overtone of these concepts is completely different as AI implies human replacement while AUI enhances human potential through appropriate, intelligent technologies (Sobczak, 2019).

In the author's opinion, the future-oriented business processes automation will definitely depend on Smart Process Automation, implementing AI, enabling workforce orchestration, robotic and cognitive automation. Therefore, the conducted literature review and RPA market analyses allow considering this technology not only as a trend but mainly as an opportunity for enterprises to achieve competitiveness and shape proper organisational culture. Relieved of tedious and repetitive tasks, which usually waste their potential, employees can freely use their creativity.

Following the introduction of software robots to enterprises, an interdisciplinary area of research called robonomics emerged, which is mainly concerned with advanced technologies (using AI) of automation and robotisation from the perspective of their economic impact on organisations (Ivanov, 2017). Recently, the RPA conception was extended towards its conjunction with artificial intelligence, cognitive computing, process mining and data analytics. The introduction of advanced digital technologies allows RPA to be reallocated from performing repetitive and error-prone routines in business processes towards more complex knowledge-intensive and value-adding tasks (Ivancic et al., 2019).

Conclusions

Robotisation of processes raises emotions due to many different reasons. Some authors claim that robotics is a progressive social revolution, perhaps even the same as the Information Age or the Industrial Age (Forbes, 2017). The main objectives for business process automation are increasing the efficiency and revenue as well as reducing the overhead. Digital transformation of the 21st century would be impossible without robots and automation. Therefore, it seems that RPA as a concept and class of information systems will be gaining importance in the modern business environment, in which information is processed on an unprecedented scale.

RPA is more often practically implemented than investigated by research. Responding to the call by van der Aalst (van der Aalst et al., 2018), the paper also aims to initiate the academic discourse about RPA. This paper is conceptual (Gilson & Goldberg, 2015) as it discusses the fundamentals of the concept, synthesises knowledge of technology, and presents it in a new context to constitute a foundation for new research aimed at filling knowledge gaps in this area. The conducted literature analysis identified a theoretical and empirical research gap. One of the possible directions for future research is the investigation of direct and indirect effects of RPA on organisational performance. It is essential to discuss differences, similarities, and complementarities between RPA and similar technologies and approaches to business process management (BPM/BPMS). Researchers should seek to determine strategic approaches to RPA solutions that could be chosen to design the implementation process and the ongoing management of software robots in a successful and sustainable way. As with any major decision in an organisation, decision-making in the context of RPA must follow a strategic approach.

RPA is one of the automation tools that need to be integrated with other tools, such as BPMS, and in the near future, with cognitive automation tools (software robots are expected to learn and mimic human behaviour and handle complex use cases). For long-term development, RPA needs to be extended beyond the rigid rule-based methods. Therefore, the combination of RPA with artificial intelligence (mainly including machine learning techniques), big data, and the data mining concept are foreseen to generate and execute refined process models. This is referred to as smart process automation, which is a possible extension of RPA.

Robotisation of business processes on a large scale must be treated as an organisational and technological change, which leads to the emerging hybrid work environment (business application, software robots, processes and procedures and people with specific competences and skills). There is certainly no reason to fear that robots will banish people. On the contrary — employees and machines (software robots) will become one hybrid environment. It should also be emphasised that working in such an environment requires picking up many gauntlets. Until now, managers have focused only on HR management, often without excavating details of the technology. The point is, they will have to supervise teams consisting of both people as well as bots (Sobczak, 2019). Considering a human labour perspective, researchers should also deal with RPA's potential future impacts on employees and their perceptions of software robots, mainly trust in technology (Ejdys, 2018), human–robot interactions and collaboration. In this context, strategic initiatives to deploy RPA should consider employee engagement, the development of skills and competencies, and sourcing of decisions. With changing areas of responsibility, enterprises should rethink employee roles (Vedder & Guynes, 2016).

Although RPA will not eliminate entire jobs, it is expected to have an effect on some jobs. In 2020, the United Nations and the World Economic Forum are expected to discuss RPA in the context of jobs, wages and global economics. Individual countries will also become increasingly interested in the effects of automation on societies. Analysts are also convinced that "developing a digital transformation strategy that encourages an automation-first mindset will be vital for a company's future survival RPA is just one component of a broader intelligent automation platform that must be combined with other automation technologies". Adopting an "automation first" mindset is the initial step for implementing digital transformation in a company. Such an approach to the problem enables an enterprise to develop, serve customers better and operate more efficiently and effectively. It unburdens employees from mundane, repetitive work, allowing them to focus on problem-solving and value-creation.

One of the most important challenges is identifying processes suitable for RPA automation (Leopold et al., 2018). It is critical to select an appropriate process for automation to avoid increased inefficiency and failure (Gadre et al., 2017). Aiming to determine appropriate processes for automation, it is necessary to establish criteria that help to recognise the suitability of a process for RPA. A link with process mining also seems obvious as process identification can be used to learn "by example" to subsequently detect process fragments that are suitable for RPA (van der Aalst et al., 2018). Future research by the author will include the development of a set of key criteria for business processes selection suitable for robotisation with the help of RPA tools (process mining) and the development of a conceptual framework for assessing the readiness of a service enterprise to implement such solutions. Moreover the fundamentals of cognitive automation and human–robot interactions and collaboration will be deepened.

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Defining stages of the Industry 4.0 adoption via indicator sets

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ABSTRACT
As Industry 4.0 offers significant productivity improvements, its relevance has grown across various organisations. While it captures the attention of both the industry and the academia, very few efforts have been made to streamline useful indicators across stages of its implementation. Such work facilitates the development of strategies that are appropriate for a specific stage of implementation; therefore, it would be significant to a variety of stakeholders. As a result, this paper aims to establish an indicator system for adopting Industry 4.0 within the context of the three stages of the innovation adoption: (i) pre-adoption, (ii) adoption, and (iii) post-adoption. First, a comprehensive review was performed with a search expanding into the literature on innovation and technology adoption. Second, the resulting indicators were filtered for relevance, redundancy, description, and thorough focus discussions. Finally, they were categorised by their stage of adoption. From 469 innovation adoption indicators found in the literature, this work identified a total of 62 indicators relevant for the Industry 4.0 adoption, in which 11, 14, and 37 of them comprised the three stages, respectively. Case studies from two manufacturing firms in the Philippines were reported to demonstrate the applicability of the proposed indicator system. This work pioneers the establishment of an indicator system for the Industry 4.0 adoption and the classification of such indicators into three stages — pre-adoption, adoption, and post-adoption — which would serve as a framework for decision-makers, practitioners, and stakeholders in planning, strategy development, resource allocation, and performance evaluation of the Industry 4.0 adoption.

KEY WORDS
Industry 4.0, indicators, stages of adoption, management of Industry 4.0

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Introduction

In various organisations, the quick shift towards digital transformation has been primarily modifying business models, production processes, and corporate governance methods. As such, the rapid stride of technological advancement necessitates the decision to adopt innovations. Consequently, companies that have more innovation capabilities are also more able to recognise early the extent of the influence by the digital transformation on their business models as well as the contribution they can get from the information derived from their initiatives (OECD, 2005).

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The potentials offered by the increasing application of digitisation are reshaping the competitive dispositions of organisations, their customer and employee interrelation, and market positioning (Castelo-Branco et al., 2019). Hence, the capability of firms to grasp the concepts and applications behind digitisation has become crucial in gaining competitive advantage (Bleicher & Stanley, 2016).

The area of digital transformation contains a dimension that has been capturing the interest of academics and practitioners concerning the prospects and the effect of applying digitisation to organisations, which is commonly termed Industry 4.0 (I4.0). Rapid changes brought by I4.0 modified how an organisation operates. Primarily, the principle of I4.0 is the interconnectivity of digital technologies, devices, and processes, which enables the operation of autonomous manufacturing models, able to perform in a decentralised decision setting with minimal human interference, and capable of connectedly working together along the stages of the production process and across several stages of the supply chain (Castelo-Branco et al., 2019).

Innovations and changes in corporate environments significantly affect a firm's performance and sustainability. Furthermore, firms need to create appropriate strategies to aid their preparation for future emerging industrial developments, for instance, I4.0. This is especially relevant when the path towards a completely digital manufacturing enterprise is ambiguous (Lee et al., 2013). In fact, the current I4.0 trend has not yet been recognised by several industry leaders. Some do acknowledge this industry trend, however, they are generally unaware of the initiatives for making their organisations prepared for the I4.0 implementation (Rajnai & Kocsis, 2018). Nevertheless, converting a firm into a completely digital enterprise requires the alteration of organisation's strategies, which is an essential choice to make aiming for the success and sustainability of competitive advantage in the digital transformation process essential for I4.0 (Vogel-Heuser & Hess, 2016). To this end, establishing an indicator system proves to be relevant for appropriately steering an organisation's strategic direction and evaluating ideas and concepts further, especially across the stages of the process of innovation.

Various studies on the topic of I4.0 focused on such issues as streamlining the opportunities or challenges of I4.0 (Kamble et al., 2018; Glass et al., 2018; Müller et al., 2018), I4.0 development indicators (Alekseev et al., 2018), antecedents to the use of I4.0 (Müller, 2019), critical success factors (de Sousa Jabbour et al., 2018), and, more abundantly, on the aspect of technicality and key technologies, such as cyber-physical systems (CPS) (Lee et al., 2015; Alguliyev et al., 2018), the Internet of Things (IoT) (Hsu and Lin, 2016), cloud computing (Priyadarshinee et al., 2017; Hassan, 2017; Siderska & Mubarok, 2018), and smart manufacturing (Tao et al., 2018). However, despite current studies, the focus is rarely placed on I4.0 indicators, even though the topic requires further analysis.

For most companies, the establishment of indicators is deemed crucial for better management and control of emerging concepts and ideas regarding innovation. Furthermore, indicators are significant for an appropriate and efficient allocation of resources, and assessment of performance at a specific innovation stage (Dewangan & Godse, 2014). In policymaking initiatives, having an appropriate set of indicators can aid an organisation's status and level of the I4.0 implementation, further recognising the relevance and suitability of innovation activities completed to realise the full implementation of I4.0. Given the necessity to improve and develop an indicator system for I4.0, the present study attempts to provide a set of indicators behind the performance management in the implementation of I4.0 tailored according to the stages of innovation (OECD, 2005; Birchall et al., 2011).

Consequently, it is essential to consider arguments used by various innovation scholars over the past two decades, such as Rogers (1995), Hameed et al. (2012), and Caiazza and Volpe (2016), indicating that any innovation adoption occurs in stages. For instance, Hameed et al. (2012) argued that the innovation process could be summarised in three stages: pre-adoption, adoption-decision, and post-adoption. Thus, the management of the I4.0 implementation should follow a stage-based approach since different concerns prevail at different stages (Hameed et al., 2012). The understanding of the issues particular to different stages enables firms to suitably craft programmes and initiatives for gaining competitive advantage, making resource allocation decisions, and long-term planning. The classification of innovation maturity into stages has demonstrated its usefulness in business, as demonstrated by the current literature. For example, Solis (2016) classified digital transformation maturity into six levels: (1) business as usual, (2) test and learn, (3) systemise, (4) adapt or die, (5) transformed and transforming, and (6) innovate or die. Habicht et al. (2012) defined the stages of open innovation as (1) staying closed, (2) defined open innovation, (3) managed open innovation, and (4) aligned open innovation. Moreover, Ham et al. (2015) categorised the maturity of open innovation for the government into four stages: (1) semi-opened, (2) focused-opened, (3) balanced-opened, and (4) fully opened.

Unfortunately, the I4.0 implementation has not been viewed in terms of its distinct stages of adoption despite being under the umbrella of the general innovation domain. In the current literature, the I4.0 implementation has been short-sighted and fragmented as it is deliberately embedded in existing management frameworks. Such approaches diverge from the conventional innovation theory established by Rogers (1995). These approaches may fail to establish a holistic method embedded in the innovation process, which may result in haphazard implementation, waste of resources, and a myopic view of I4.0.

Thus, this work attempts to address two critical gaps in the literature: (1) treating I4.0 as an innovation process, which is described in stages, and (2) developing indicator sets for each stage of innovation. The objective of this work is to reveal indicators specific for stages of the I4.0 adoption, which would guide decision-makers in strategy development and evaluation as well as performance evaluation. Evanschitzky et al. (2012) supported the notion that indicators played significant roles in efficient resource allocation and performance evaluation. These indicators were characterised by measurable parameters that could provide valuable information (Dziallas & Blind, 2018) about the adoption capabilities and necessities of firms at each stage. Thus, in the process of I4.0 adoption, the need to identify the operational adoption indicators for each stage becomes essential. Case studies from two manufacturing firms operating in the Philippines are reported in this work to demonstrate the applicability of the proposed indicator system across all stages of innovation. A generic methodological framework is offered, but the specific mathematical toolbox that encapsulates the entire framework is reserved for future work. Without compromising generality, the used approach was derived from the outline of Xu (2006) on the linguistic arithmetic averaging operator.

The paper has six sections. This section is followed by Section 2, which rationalises the stages of innovation adoption. Section 3 discusses the methods for the selection of different adoption indicators. Adoption indicators for each stage of adoption are identified in Section 4. Section 5 elaborates on the applications of the proposed indicator sets by using case studies conducted in manufacturing firms operating in the Philippines. Finally, Section 6 presents managerial implications and concluding remarks.

1. Stages of the innovation adoption

Schumpeter (1934) first defined innovation as a combination of new or existing knowledge, resources, equipment, and other factors. In the Manual on the Measurement of Scientific and Technological Activities, this definition was adopted by OECD (2005) as the implementation of a new or significantly improved product, process, or service. Crossan and Apaydin (2010) extended the definition of innovation as "production or adoption, assimilation, and exploitation of a value-added novelty in economic and social spheres: renewal and engagement of products, services and markets; development of new methods of production; and the establishment of new management systems." The above description was simplified by Edison et al. (2013), emphasising two essential concepts: first, there must be an invention or discovery of a new idea, and second, there must be commercialisation or successful exploitation through commercialisation of such discovery. The latter description of innovation emphasises the commercialisation, which offers a better picture of I4.0 as innovation. For a more elaborate discussion on the commercialisation component of innovation, see the works of Slater and Mohr (2006), Datta et al. (2013), Datta et al. (2015), and Egorova et al. (2017). For brevity, and as the topic falls outside the scope of this work, the emphasis on commercialisation as a crucial point of innovation is not presented here.

Hermann et al. (2016) considered Industry 4.0 as a convergence between industrial production and information and communication technologies (ICT), which is comparable to technical innovation (Oesterrich & Teuteberg, 2016) and technological innovation (Kagermann et al., 2013). Kamble et al. (2018) stressed that the ICT part of I4.0 consisted of the cyber-physical system (CPS), cloud computing, and the Internet of Things. This position justifies the need to untangle the I4.0 adoption from the context of innovation adoption as the infrastructure of I4.0 is mostly ICT-based. Thus, since I4.0 occurs within the innovation context, it is apparent that any work on I4.0 must be anchored in the foundation of innovation studies. In the light of the innovation domain, van Oorschot et al. (2018) used both bibliometric coupling and co-citation analysis to map and synthesise fragmented empirical studies on innovation, which revealed the theory of Diffusion of Innovation (DOI) by Rogers as the cornerstone of innovation adoption research.

As described by Rogers (1995), innovation adoption is a process that occurs mainly from awareness or knowledge, attitude formation to persuasion to a decision to adopt or reject, then followed by implementation. Moreover, since the innovation process is usually complicated (Dodgson and Hinze, 2000), it is apparent to embrace the concept of indicators to understand innovation adoption. As claimed by Cavdar and Aydin (2015), indicators are crucial for information about things that are difficult to measure. Caiazza and Volpe (2016) asserted that indicators are indispensable to management and control of the plethora of innovative ideas and concepts. Gault (2018) highlighted that indicators could be used for monitoring and evaluation of implemented innovation policies. Likewise, Evanschitzky et al. (2012) inferred that for policy-making practices, it is significant to have accurate indicators to evaluate the proposed innovation and the impact of such innovation. On the other hand, Dziallas and Blind (2018) reported that innovation process indicators are less frequently investigated. Thus, it is crucial to unfold the complexities of the I4.0 adoption by espousing the concept of indicator sets. However, despite the importance, the identification of I4.0 indicators has not been explored in the current literature.

Relevant literature on the innovation adoption indicators, which is not specifically within the context of I4.0, reported different frameworks and phases of the innovation process. Hart et al. (2003) held that the early stages of the innovation process required different indicators in comparison with a later stage. Their notion was derived from their investigation of the new product development (NPD) process with stages that included the idea generation, concept development, building the business case, product development, market testing, and market launch. Also, in terms of a lifecycle-oriented approach (Suomala, 2004) to innovation, Dewangan and Godse (2014) argued that each phase of innovation lifecycle had its unique activities and outputs, amenable to measurement and benchmarking. Evanschitzky et al. (2012) established selection criteria for efficient resource allocation and performance evaluation at each phase of the innovation process. Lombardi et al. (2013) introduced a novel framework for classifying smart city components and performance indicators. They clustered the indicators as smart governance, smart human capital; smart environment; smart living, and smart economy. Dziallas and Blind (2018) introduced process innovation indicators and factors in the framework of the stage-gate system introduced by Cooper (1990). Similarly, Miremadi et al. (2018) proposed an energy innovation indicator framework that focused on the energy innovation process, covering the entire innovation chain and incorporating indicators into the specific innovation stages. However, these studies on the concept of innovation indicators did not use the model of the innovation process by Rogers categorically as the cornerstone of innovation research, as reported by van Oorschot (2018). This model was summarised from innovation studies by Damanpour and Schneider (2006) and Hameed et al. (2012) as a pre-adoption stage, adoption-decision stage, and post-adoption stage.

The pre-adoption or initiation stage involves activities similar to need or problem recognition, information search on the innovation's existence, forming an attitude towards the innovation, and proposing innovation for adoption (Rogers, 1995; Hinnant & O'Looney, 2003). Hence, this stage is considered as the preparatory stage of adoption. The adoption-decision stage, on the other hand, manifests acceptance or rejection of the innovative idea based on the evaluation of human and material resources and the assessment and future resource allocation if the innovative idea is accepted (Hameed et al., 2012). It is the stage, wherein the adopters have entirely accepted or rejected the innovation for actual implementation. The post-adoption stage, also known as the implementation stage, encompasses possession, validation, acceptance, and sustained real use of the innovation (Hameed et al., 2012).

Moreover, Zhu et al. (2006), grounded in the DOI theory and the Technology-Organisation-Environment (TOE) framework, established four innovation characteristics (relative advantage, compatibility, costs, and security concern) and four contextual factors (technology competence, organisation size, competitive pressure, and partner readiness) as determinants of the post-adoption usage. It is the stage, wherein the adopters have applied the innovation in the system with full acceptance of the benefits and risks brought about by such adoption. With the four characteristics of innovation, I4.0 can be considered an innovation. First, it exhibits a relative advantage, as found by Arnold et al. (2018). Second, through decentralisation, I4.0 becomes easily compatible with different organisations, as argued by Shamim et al. (2016). Third, I4.0 is highly related to different types of costs (e.g., production or quality) in a positive sense (Rojko, 2017). Finally, I4.0 has been associated with several security concerns, particularly cyber and information security (Wegner et al., 2017). Having established that I4.0 is an innovation, it follows that the three stages of the adoption of innovation, as prescribed by Rogers (1995), can also be used to categorise the stages of its adoption.

2. Indicators of the Industry 4.0 implementation

This section illustrates how to establish the final list of indicators by way of a comprehensive review of related literature and demonstrates the applicability of the list by conducting relevant case studies. Specifically, this process begins with a keyword search in four core databases, followed by a collection of articles and content analysis. Then, indicators are selected according to the context relevance and redundancy.

2.1. Article selection process and content analysis

A keyword search was performed in four core databases to gather relevant articles in the literature, which potentially discusses the indicator system for I4.0. As the development of I4.0 is yet an emerging domain and is still at its early stages (Issa et al., 2018), the search was expanded from I4.0-specific applications to the general technology and innovation adoption. The primary keywords used were: "digital transformation", "industry 4.0", "industry 4.0 adoption", "innovation", "innovation adoption", "technology", "technology adoption"; together with supplementary keywords such as "indicators" and "predictors" The study used the following databases: Elsevier's ScienceDirect and Scopus, Taylor & Francis' www.tandfonline.com, and Springer's SpringerLink. To reach a comprehensive coverage of publications related to the indicators of the I4.0 adoption, journal articles, and conference proceedings were also obtained from these databases. In the following step, a content analysis was performed to extract prospective indicators on identified articles. Articles that do not ultimately provide related indicators were excluded.

2.2. Selection of indicators

A comprehensive list of indicators was generated from a variety of innovation studies, having numerical metrics as part of their methodology. However, in the context of I4.0, no present study was able to develop a set of indicators to assess the I4.0 implementation at different stages. Thus, a significant challenge was to select an appropriate set of indicators from the general system of innovation and technology adoption. Addressing the challenge, several criteria were used for the selection and construction of indicators. Four criteria were used in the screening process to select appropriate indicators. Miremadi, Saboohi and Jacobsson (2018) developed general criteria for the selection of indicators in the context of innovation systems. They used this set of criteria as it covered approximately all factors in the relevant literature (Miremadi, Saboohi & Jacobsson, 2018). To measure the I4.0 implementation, indicators must be understandable, available, relevant, and measurable. First, an indicator is considered understandable if it is straightforward, simple, and provides ease of understanding. Second, an indicator is available if data and information are accessible. Availability ensures that the value of a specific indicator is obtainable from a company's information system. Third, indicators are deemed relevant if they satisfy the goal of assessing the level of the I4.0 implementation and if they point to the characteristics or nature of activities per stage. Fourth, indicators must be measurable following an existing scientific measurement approach (e.g., surveys).

An initial list of indicators was generated from a literature review on a variety of technology and innovation adoption applications, as shown in Table 1. In this work, an indicator was defined as a source of information, from which problems could be detected in the application of innovation (Borras & Edquist, 2013). A total of 469 indicators were collected. At the outset, these indicators contained literal redundancies of terminologies in different sources. Consequently, such redundant indicators were excluded, and this process yielded 90 candidate indicators. Afterwards, an appropriate description of each indicator was provided, indicating primary sources, from which they were extracted. In cases of insufficiency, supplementary or secondary sources (i.e., related journal articles and scholarly books) were used. From the initial list of indicators with descriptions, specific terms were found to be synonymous. Indicators implying a synonymous meaning were treated as redundant, thus, excluded. Focus meetings were then conducted to qualify a final list of indicators.

Descriptions of each indicator were carefully assessed. Each indicator was then assessed using the four criteria, focusing on its understandability, availability, relevance, and measurability. Subsequently, following the process of a thorough assessment, indicators that did not meet the four criteria were rejected. This process generated a final list of 62 indicators of the I4.0 adoption. An initial list was then categorised according to stages of adoption from initiation, adoption-decision, and implementation (i.e., pre-adoption, adoption, and post-adoption, respectively) (Hameed et al., 2012). These stages were an essential determinant to reflect the entire innovation process and to control the applicability of each indicator (Table 2).

Table 1 presents the number of extracted indicators, their application, and sources to provide an overview of the initial listing of I4.0 indicators used in this paper. The first column indicates authors from whom candidate I4.0 indicators were extracted. Papers listed under the label "reference indicators" indicate sources used to collate respective innovation or I4.0 indicators. Hence, "reference indicators" are the sources of performed compilation. For instance, to explore and discuss I4.0 technologies, Lu (2017) collated I4.0 indicators from Jazdi (2014), Stock and Seliger (2016) and Wang et al. (2016), among others. Moreover, the second column comprises the field of

Tab. 1. Numbers of indicators generated from literature with their corresponding application

Author(s)	Application	No. of generated indicators
Chor et al. (2014)	Contextual level-based innovation adoption	116
Danquah (2018)	Technology adoption and utilisation	1
Ezzi and Jarboui (2016), Yigitcanlar et al. (2017)	Financial, social, and environmental effects of innovation strategy	2
Lu (2017) Reference indicators: Jazdi (2014), Stock and Seliger (2016), Wang et al. (2016), Gorecky et al. (2014), Hermann et al. (2016), Kolberg and Zühlke (2015)	Industry 4.0 technologies	7
Lee et al. (2015)	Industry 4.0 technologies (CPS)	1
Tao et al. (2018)	Industry 4.0 technologies (smart manufacturing)	1
Hameed et al. (2012) Reference indicators: Gopalakrishnan and Damanpour (1997), Rogers (1995), Meyer and Goes (1988)	IT innovation adoption	124
Jeyaraj et al. (2006), Pilke (2004)	Individual and organisational-based IT innovation adoption	94
Alguliyev et al. (2018)	Industry 4.0 technologies (CPS)	14
Attaran (2017)	Industry 4.0 technologies (additive manufacturing)	5
Hassan (2017)	Industry 4.0 technologies (cloud computing adoption)	3
Hsu and Lin (2016)	Industry 4.0 technologies (adoption of the Internet of Things)	6
Letia and Kilyen (2018)	Industry 4.0 technologies (CPS)	9
Lopez and Rubio (2018)	Industry 4.0 technologies (integration of CPS and cloud computing)	2
Molina and Jacob (2017)	Industry 4.0 technologies (CPS)	1
Monostori et al. (2016)	Industry 4.0 technologies (CPS)	4
Priyadarshinee et al. (2017)	Industry 4.0 technologies (cloud computing adoption)	50
Salleh et al. (2017)	Software functionality service	1
Sharma et al. (2016)	Industry 4.0 technologies (cloud computing adoption)	6
Sung (2018)	Industry 4.0 levers	17
Terziyan et al. (2018)	Industry 4.0 technologies (artificial intelligence)	5
	TOTAL	**469**

application used by a corresponding author (e.g., Chor et al. (2014), Lu (2017), and Hameed et al. (2017)) to demonstrate roles of indicators. The third column displays the number of indicators extracted from corresponding works to comprise the initial list of I4.0 indicators in this paper. The information displayed in Column 3 (Table 1) demonstrates that most of the extracted indicators came from the general innovation literature. For example, 116 indicators were extracted from Chor et al. (2014). The result stems from the attribution of I4.0 to innovations in the current literature, as pointed out by Morrar et al. (2017), Liao (2017), Brettel et al. (2014), and Almada-Lobo (2016), among others. Based on such claims in the literature, placing general innovation indicators in the context of I4.0 is validated by its innovation status.

2.3. Application of case studies

To illustrate the use of the developed indicator system to assess the I4.0 implementation, case studies involving two manufacturing firms in the Philippines were conducted. The developed indicator set for each stage of the I4.0 adoption intended to assess the degree, to which a firm was positioned, given its current I4.0 implementation. By using the indicator sets, this work offered a general methodological approach, which attempted to generate the value indicating the performance or maturity of the firm at any given stage. The performance or maturity value, now denoted as a general index, provides a snapshot of the performance of the firm at an I4.0 adoption stage at a given time. Note that the quality of this snapshot is highly dependent on the completeness and quality of the information used in the evaluation process, and the level of information granularity of a specific applied methodology. The methodological framework starts with the assignment of weights for the indicators of a given stage. Weight assignment could be carried out using multiple criteria decision-making methods (e.g., analytic hierarchy process, best–worst method, simple average weighting), expert opinion, Delphi method, group decision-making techniques, etc. Once the appropriate I4.0 adoption stage is determined for the firm, the performance or maturity of the firm is assessed against each indicator of the stage, using a specified evaluation scale. The results of the second process are the performance values of the firm for all indicators. Then, using a specified aggregation technique, these performance values are aggregated homogeneously. The aggregation process provides a general dimensionless index that describes the overall performance of the firm at a given stage. Although this work offers the general methodological framework, the specific methodology that embodies the framework is left at the discretion of the firm or its analyst. A detailed procedure in assessing indicators under each I4.0 adoption stage is presented as follows. Note that the proposed procedure is recommendatory, not absolute. A thorough analysis of the most appropriate methodology that maximises the quality of information used in the evaluation process is out of the scope of this work. The following procedure is presented to demonstrate the use of the proposed indicator system in a real-life application:

Step 1: Attain the performance of the indicator. Industry experts firstly identify the current stage of adoption (i.e., pre-adoption, adoption, and post-adoption) and further elicit their judgment on each indicator's performance with respect to the perceived adoption stage, using linguistic scales "very poor", "poor", "fair", "good", and "very good", whichever is applicable.

Step 2: Translate the performance of the indicator into a numerical value, according to Xu (2006). For a given linguistic set, S, a corresponding s_α, the numerical value is attained for each indicator as in (1),

$$S = \{s_\alpha | \alpha = -t, \dots, -1, 0, 1, \dots, t\} \quad (1)$$

that is (2),

$$S = \{s_{-2} = \text{very poor}, s_{-1} = \text{poor}, s_0 = \text{fair}, s_1 = \text{good}, s_2 = \text{very good}\} \quad (2)$$

correspondingly, these indicator indices will be used to obtain the overall performance of firms at a particular I4.0 adoption stage.

Step 3: Define the overall performance of a firm as regards the I4.0 adoption. The indices of previously generated indicators are then aggregated as shown in (3) to arrive at a general index on the performance of firms as regards the I4.0 implementation,

$$LWAA_\omega(s_{\alpha1}, s_{\alpha2}, \dots, s_{\alpha n}) = \omega_1 s_{\alpha1} \oplus \omega_2 s_{\alpha2} \oplus \dots \oplus \omega_n s_{\alpha n} = s_{\bar{\alpha}} \quad (3)$$

Where
$\bar{\alpha} = \sum_{j=1}^{n} \omega_j \alpha_j$, $\omega = (\omega_1, \omega_2, \dots, \omega_n)^T$
is the weight vector of the $s_{\alpha_j}(j = 1,2,\dots,n)$ and $\omega_j \in [0,1], \sum_{j=1}^{n} \omega_j = 1$, $s_{\alpha_j} \in \bar{S}$, then LWAA is referred to as the linguistic weighted arithmetic averaging (LWAA) operator. In the case of this paper, the weight vector of the s_{α_j} is assumed to be equal, thus, the average of s_{α_j} is given by (4),

$$LWAA_\omega(s_{\alpha1}, s_{\alpha2}, \dots, s_{\alpha n}) = \frac{\sum_{j=1}^{n} s_{\alpha1}, s_{\alpha2}, \dots, s_{\alpha n}}{n} \quad (4)$$

Tab. 2. Indicators for each stage of adoption

Stage of adoption	Indicator	Application	Description	References
Pre-adoption	Compatibility	Cloud computing adoption in SMEs	The degree of perception to consider the adoption of new technology when technology is recognised as compatible with work application systems	Priyadarshinee et al. (2017)
	Perceived ease of use	User IT acceptance	The degree, to which an adopter believes that using a particular system would be free of effort	Hameed (2012), Davis (1989)
	Perceived usefulness	User IT acceptance	The degree, to which an adopter pursues a particular technology to the extent at which one believes that it will improve the performance of a task	Hameed (2012), Davis (1989)
	Flow experience	User IT acceptance	The extent, to which an adopter experiences an optimal mental state of being fully immersed, focused and involved in tasks, activities, or initiatives an adopter is undertaking for the I4.0 implementation	Pilke (2004)
	Internal information sources	IT adoption by organisations	Internal information that may have been acquired at one time from previous experience and past information searches, or passively through low-involvement learning, where consumers are repeatedly exposed to marketing stimuli	Jeyaraj et al. (2006)
	External information sources	IT adoption by individuals	External information acquired from the environment, and this represents a conscious effort to seek out new information	Jeyaraj et al. (2006)
	Observability		The degree, to which the results of an innovation are observable from those who have already adopted the innovation	
	Perceived risk	IoT services adoption	The level of an adopter's uncertainty in the aspect of anticipated costs, sacrifices, and losses when a new technology is adopted	Hsu and Lin (2016)
	Perception of the term Industry 4.0	Cloud computing adoption in SMEs	The degree of an adopter's awareness of the term "Industry 4.0", and the extent, to which they evoke technology adoption	Priyadarshinee et al. (2017)
	Subjective importance of tasks	Innovation adoption	The extent, to which the importance of the task of configuring systems and satisfaction are derived and ranked relative to the importance of and satisfaction with other five tasks: face-to-face selling, sales planning, answering technical questions, administrative work, and other internal work of the corporation	Chor et al. (2014)
	Technological innovativeness	Innovation adoption; IT innovation adoption in organisations	The extent, at which organisations tap and harness technologies that lie beyond their formal boundaries	Sharma et al. (2016), Chor et al. (2014), Hameed (2012), Rogers (1995)
Adoption	Competitive price intensity	Innovation adoption	The frequency of price-cutting taking place at a particular organisation	Chor et al. (2014)
	The emergence of the global distribution network	Cloud computing adoption in SMEs	The level of existence of a mechanism that helps a supplier widen the range of targets	Priyadarshinee et al. (2017)
	CEO advocacy	Innovation adoption	The degree, to which the highest official of an organisation provides supportive actions for innovation	Chor et al. (2014)
	Financial evaluation	Assimilation of innovations in hospitals	The level of the process of evaluating various projects, budgets, businesses, and further finance-related subsidiaries to agree on their viability for investment	Meyer and Goes (1988)
	Innovation in business models	Prototypical implementation in an industrial machine; innovation of dietary supplement shops; reconfiguration tactics in electric vehicle manufacturers	The extent, to which new technologies or business ideas are translated into new business models including the choice of the organisational type, planning method, the approach to the reconfiguration and development of a convincing value proposition	Jazdi (2014), Christensen et al. (2016), Sosna et al. (2010), Bohnsack and Pinkse (2017)

	Competitive pressure	Cloud computing adoption in SMEs	The level of pressure made by competitors and felt by the organisation to adopt a new technology	Priyadarshinee et al. (2017)
	Incentives for the I4.0 adoption	Innovation adoption	The degree, to which the public sector or government provide an effective incentive scheme and share a portion of innovation financial risks through the provision of financial subsidies, low-interest and long-term loans and tax reduction to primarily provide an innovative and competitive avenue for I4.0 adopters	Yigitcanlar et al. (2017)
	The geographic location of an organisation	Diffusion of knowledge in plant biotechnology; innovation performance of technology-intensive firms	The level, to which the geographical clustering among I4.0 adopters positively influences tacit knowledge exchange through simplified interaction in the form of formal or informal contacts, further characterised by a frequency of interactions and creation of networks for the realisation of innovation	Gallaud and Torre (2005), Martinez-Noya and Garcia-Canal (2017)
	Customer interaction	A dynamic evolutionary model of demand in long-distance telecommunications services	The degree of advertising, marketing, sales, and customer support activities performed by an organisation to interact with its customers	Manral (2010)
	Reputation of suppliers	Cloud computing adoption in SMEs	The extent of perceptual representation of an organisation's past actions and prospects that describe the organisation's overall appeal to all of its key stakeholders when compared with other leading rivals	Priyadarshinee et al. (2017)
	Size of an organisation	Cloud computing adoption in SMEs	The extent, to which I4.0 adopters exhibit tolerance for bearing the cost and the risk of adopting innovations, given the adopter's resources, the volume of transactions, and the size of the workforce	Priyadarshinee et al. (2017)
	Information systems infrastructure	IT adoption by organisations	The degree of pervasiveness, power, and tight integration among elements of information infrastructure to transfer, store and retrieve, and process information	Jeyaraj et al. (2006)
	Technical support and expertise	Assimilation of innovations in hospitals; user IT acceptance	The level of proficiency of an I4.0 adopter in the aspect of information technology installation, operation, maintenance, network administration, and security	Meyer and Goes (1988), Hameed (2012)
	Type of industry	IT adoption by organisations	An industry's level of characterisation by the level of complexity of operations, which calls for the improvement of competitive advantage and the development of the Industry 4.0 competency	Jeyaraj et al. (2006)
Post-adoption	Access to I4.0 technologies	Cloud computing adoption in SMEs; smart manufacturing	The degree of availability and acquisition of I4.0 technologies among I4.0 adopters, such as IoT, CPS, smart manufacturing, and cloud computing	Priyadarshinee et al. (2017), Kang et al. (2016)
	Adaptivity by plug-and-work	Implementation of CPS and CPPS in manufacturing; different levels of applications (e.g., sensor level)	The extent, to which technologies control relevant entities within the production system through convenient plugged in/connectivity to start operations without changing the control applications for the rest of the production system	Monostori et al. (2016)
	Auditability	Cloud computing adoption in SMEs	The system's degree of efficiency in finding any unexpected information behaviour upon request of the customer to increase trustworthiness	Priyadarshinee et al. (2017)
	Culture of change	IT adoption by organisations	The extent, to which the organisation responds to a perceived change in demands on the core tasks when aiming at developing a service business	Jeyaraj et al. (2006)
	Customer co-creation	Conceptual typology ad research agenda	The extent, to which I4.0 adopters perform a collaborative new product development activity, which makes consumers actively contribute and select various elements of a new product offering	Sung (2018), O'Hern and Rindfleisch (2010)

	Data lifecycle	CPS implementation in factories	The extent, to which elements in the information system can complete the journey of data collection, transmission, storage, pre-processing, filtering, analysis, mining, visualisation, and application	Lee et al. (2015), Tao et al. (2018)
	Decentralisation	Use of patented intelligence in various fields (e.g., collaborative mass customisation of short lifecycle products)	The extent, to which decision-making is dispersed in an organisation, giving employees greater autonomy and responsibility, and consequently increasing internal information flow	Terziyan et al. (2018)
	Degree of autonomy	Use of CPS in a distributed control system for an urban vehicle traffic	The level of self-governing capability of a machine with embedded knowledge processing that allows independent decision-making	Letia and Kilyen (2018), Tweedale (2015)
	Degree of integration	Innovation adoption; user IT acceptance; technology planning process in a private academic institution	The extent of integrating technology into an organisation for effective and diffused use of technology and getting management to the established standards	Hameed (2012), Chor et al. (2014), Gülbahar (2007)
	Dependability	Creation of CPS; estimation of dependability metrics in virtual network environments	The degree of reliability and availability of information technology tools, which directly impact the quality of service	Alguliyev et al. (2018), Lira et al. (2015)
	Economies of scale	Cloud computing adoption in SMEs	The level of cost advantage obtained by a firm when the cost per unit of output decreases as production quantity increases	Priyadarshinee et al. (2017)
	Financial leverage	Impact of innovation strategy in high-level-research companies	The degree, to which an organisation generates profits from the implementation of innovation strategies	Ezzi and Jarboui (2016)
	Formalisation of systems development	Application of formalisation	The extent, to which an I4.0 adopter can create formally-defined, brand-named, or published development methodologies aimed at descriptions of the current work of users and the organisation, functional requirement specifications, technical design, functional design, code, technical conversion plan, and functional conversion plan, to name a few	Mathiassen and Munk-Madsen (2007)
	The functionality of service quality	Use of software functionality service in diverse type network technologies (e.g., 3G)	The degree of fitness for a piece of software or how it compares to competitors in the marketplace as a worthwhile product	Salleh et al. (2017)
	Human in/outside the loop	Smart process control in an experimental office building	The degree of information technologies to integrate humans in the process control loop, that is, interacting with a distant system to accomplish a given task	Aduda et al. (2014)
	Information intensity	Effect on various industries' competitive advantage	The level of intellectual work done by I4.0 adopters as they conduct their affairs	Sabherwal and King (1991)
	Intelligent lots	Batch scheduling problem	The extent, to which technologies deal with batch scheduling problems	Li et al. (2012)
	Interoperability	Cloud computing adoption in SMEs	The degree of using computational tools to facilitate the flow of work and coordination between organisations	Priyadarshinee et al. (2017)
	Knowledge transformation	Innovation adoption	The number of new product ideas or projects initiated by an organisation	Chor et al. (2014)
	Machine flexibility	Classification of flexible manufacturing system types	A machine's degree of ease in making the changes required to produce a given set of part types	Browne et al. (1984)
	Maintainability		The degree of efficiency, to which an item will be retained in or restored to a specified condition within a given period when prescribed procedures and resources perform maintenance	Blanchard et al. (1995)
	Manager risk tolerance	Firms at a particular stock price and firm size data	The degree of I4.0 adopters' risk aversion and risk perception, which plays an essential role in the decision-making by managers	Frijns et al. (2013)

	Multilingualism	IT adoption by organisations	The degree of I4.0 technologies to support multiple languages for effective delivery of information and knowledge in CPS	Jeyaraj et al. (2006)
	Operational risk		The degree of loss risk from inadequate or failed internal processes, people, and systems, or external events	Hoffman (2002)
	Organisational efficiency	The stochastic frontier analysis employed by nations	The level, to which I4.0 adopters adopt and adapt the existing technology from world technology leaders and successfully apply it domestically	Danquah (2018)
	Organisational performance	Empirical data analysis on the role of organisational culture to the improvement of organisational performance	The extent, to which an organisation achieves set objectives of retaining profits, having a competitive edge, increasing market share, and maintaining long-term survival, which depends on the use of applicable organisational strategies and action plans	Oyemomi et al. (2019)
	Partnerships	Cloud computing adoption in SMEs	The degree, to which I4.0 adopter and suppliers work together to improve their service	Priyadarshinee et al. (2017)
	Performing trial for the organisation of innovation	Analysis of innovation research in economics, organisational sociology, and technology management	The degree, to which an innovation may be experimented with on a limited basis	Gopalakrishnan and Damanpour (1997)
	Real-time capability	Use of patented intelligence in various fields (e.g., collaborative mass customisation of short lifecycle products)	The level of a system's ability to update information at the same rate as the event happens	Terziyan et al. (2018)
	Reduced operational cost	Road-mapping process of a manufacturer of medical equipment and consumables	The extent, to which a resultant cost improvement is achieved when innovation is implemented	Issar and Navon (2016)
	Remote monitoring and control capability	Conceptual typology ad research agenda	The degree of a system's capability to control large or complex facilities, such as factories, power plants, network operation centres, airports, and spacecraft with some degree of automation	Sung (2018)
	Research & development intensity	Innovation adoption	The number of organisation-financed business-unit research projects and development expenditures, which are expressed as a percentage of business unit sales and transfers over a fixed period	Chor et al. (2014)
	Resiliency	Large scale surveys conducted among IT professionals and academics	The extent, to which data centres can withstand any cyber-attacks, floods, fire, theft, server and network failures and natural disasters without losing the ability to provide services or, more importantly, their data	Chang et al. (2016)
	Supply chain integration	User IT acceptance	The degree, to which an organisation strategically collaborates with its supply chain partners and manages intra and inter-organisation processes to achieve effective and efficient flows of products, services, information, money, and decisions, to provide the maximum value to its customers	Hameed (2012)
	System robustness	Creation of CPS	The extent of the ability of the system to cope with errors during the execution and cope with erroneous inputs	Alguliyev et al. (2018)
	Usability	Cloud computing adoption in SMEs	The degree, to which a specific user can use technology for specific organisations with the intent of reaching precise objectives with efficiency, effectiveness, and satisfaction in a determined context	Priyadarshinee et al. (2017), Letia and Kilyen (2018)
	Work simplification	IT adoption by organisations	The degree, to which information technology replaces the mental component of work particularly in manufacturing applications	Jeyaraj et al. (2006)

3. Indicators for each stage of adoption

Many efforts were put into establishing the indicators of innovation, which resulted in a long endeavour in the domain of application, reflected in the relevant literature (Moore & Benbasat, 1991; Song et al., 2014). Notably, these indicators are used to answer the following questions: (i) how aware is a potential adopter of the innovation, and how is the innovation perceived? (ii) how ready is a potential adopter for the innovation and will the innovation be accepted?, and (iii) will an adopter continue the innovation if it is accepted? It can be inferred that the literature primarily revolves around these three questions. As such, the questions result lead to the stages of innovation adoption. In the literature, several scholars emphasise that innovation adoption is a process rather than an event, and different concerns may be predominant at different stages; hence, categorising the innovation adoption at such stages become relevant (Hameed et al., 2012). In this paper, the stages of adoption are categorised as pre-adoption, adoption, and post-adoption, together with respective identified indicators. Note that the indicators presented in this work are not directly measurable because they use metrics for the basic unit of measurement. Thus, an indicator may be represented by more than one metric depending on the firm or the industry under consideration. The context of the I4.0 implementation involves several cutting-edge technologies (e.g., sensor technology, robotics, etc.). However, these technologies are not explicitly represented by these indicators as they are considered as metrics in the proposed indicator system framework. Note that identifying the metrics for each indicator is out of the scope of this work. These metrics are highly case-dependent and proposing such metrics may limit the flexibility of the proposed framework.

3.1. Pre-adoption stage

It can be seen that the first question stated previously underlies the pre-adoption stage. The pre-adoption stage involves all other conditions needed for the adoption of innovation before the evaluation of the decision is made to adopt or reject the innovation (Miranda et al., 2016). As Rogers (1995) puts it, the pre-adoption stage involves the previous conditions for adoption, knowledge or awareness of the innovation, and the perception of the potential adopter by acquiring more profound knowledge on the innovation. Inherently, adoption decisions usually come from information acquisition periods, which is implicit in technological innovations (Dimara & Skuras, 2003). In the relevant literature, several scholars infer that the lack of awareness of innovation may explain the reason why its widespread adoption does not occur (Dimara & Skuras, 2003).

The degree of awareness of I4.0 can be acquired depending on the attitude of stakeholders towards the innovation. One of the reasons why attitude plays a vital role in determining the degree of awareness is because it dictates the optimism or pessimism of potential adopters (Kerschner & Ehlers, 2016). One of the most straightforward indicators that show the awareness of I4.0 is the perception of the term "Industry 4.0" (Priyadarshinee et al., 2017). Although the literature offers no strong support to the way the term used to describe an innovation affects its adoption, several papers consider the name significant in creating different perceptions or self-concepts (Garwood et al., 1980). On the other hand, perceived usefulness, perceived ease of use, relative advantage, trialability, observability, compatibility, and complexity, are indicators strongly supported in the literature and related to the perception of potential adopters (Rogers, 1995).

For instance, the perceived relative advantage is considered a sine qua non or necessary for adoption (Greenhalgh et al., 2004). If users do not perceive a relative advantage of innovation, it is generally not adopted (Rogers, 1995). However, although considered to be critically important, it does not guarantee widespread adoption, thus, suggesting the need to look into other factors (Greenhalgh et al., 2004). Trialability — the extent, at which an innovation can be tried on a limited basis — is also strongly supported by many scholars in the literature (Miranda et al., 2016). It is strongly argued that although being able to test the innovation on a smaller sample space does not guarantee success when applied at a larger scale, it increases the confidence of adopters in the innovation (Plsek, 2003). Rogers (1995) argues that it is positively linked to the adoption of an innovation.

Aside from directly testing the innovation, observing the innovation already adopted by others may also affect the perception of potential adopters (Miranda et al., 2016). Potential adopters use a risk-reduction strategy of seeking information from others who have already adopted the innovation of interest because adopters are usually faced with uncertainty about the consequences of their decisions, which contributes to their perceived risk (Mehrad & Mohammadi, 2017). It must be noted that trialability and observability are different. Trialability involves direct testing of innovation, and observability involves indirect testing of the innovation through others who have adopted the innovation.

Similarly, another important indicator of innovation adoption is compatibility or the degree of how accustomed an innovation is to existing standards, norms, and values of potential adopters (Greenhalgh et al., 2004). Many scholars argue that compatibility may significantly predict whether innovation will be accepted or not (Greenhalgh et al., 2004). For instance, if a government agency intends to make their citizens use services online, they must provide information and services in a manner that is consistent with other ways citizens have dealt with the government, e.g., online forms should resemble paper forms that citizens are familiar with (Rogers, 1995; Joia et al., 2016). If innovation results in actions that are very different from the existing practice, potential adopters perceive it as risky, thus, possibly rejecting the innovation (Joia et al., 2016). Likewise, if innovation is perceived to be highly sophisticated, potential adopters will likely reject it (Agarwal & Prasad, 1998; Greenhalgh et al., 2004). A complex system is one that cannot be broken down into manageable parts. Several scholars claim that most organisations that opt for innovation operate in such a manner if not appropriately managed; thus, they may cause a negative perception for potential adopters (Szczerbicki, 2008). To this end, complexity plays a crucial role in indicating the perception of potential I4.0 adopters.

Several scholars also point out the importance of communication channels used in spreading information about the innovation, which contributes to the perception of potential adopters (Agarwal & Prasad, 1998). This result was found to be significant by scholars in relevant fields (Adegbola & Gardebroek, 2007). Mainly, Adegbola & Gardebroek (2007) found that when the information about the innovation was spread through external sources (e.g., knowledgeable external sources) adopters tended to have a more favourable perception of the innovation than when it was spread through internal sources (e.g., adopters who were still in the process of adoption). Hence, the perceptions of potential I4.0 adopters can be affected by the flow experience of I4.0, the emergence of global distribution networks, and some information sources.

The pre-adoption stage is concerned mainly with perceptions of potential adopters, which result from acquired awareness and more profound knowledge of I4.0. Technological innovativeness, unlike the indicators mentioned above, is more of an inherent characteristic of potential adopters rather than one generated as a result of acquired awareness. Moreover, it plays a vital role in connecting the pre-adoption (perception) indicators to the adoption (persuasion) indicators of I4.0 (Agarwal & Prasad, 1998).

3.2. Adoption stage

The adoption stage encompasses the period, in which the decision unit is engaged in activities that lead to the choice to adopt or reject innovation, otherwise known as the decision stage (Miranda et al., 2016). In contrast to the pre-adoption stage, the adoption stage involves the persuasion phase of the organisation to decide if innovation must be adopted or rejected (Miranda et al., 2016). In other words, it comprises activities (e.g., financial, technical, and strategic) that evaluate the readiness of systems to implement I4.0 in an organisation (Hameed et al., 2012). This section discusses the adoption stage indicators.

Financial evaluation activities are a straightforward indicator of the readiness for innovation (Quevedo et al., 2017). It is common practice for managers to evaluate the risks of innovation projects, mainly financial risks, since they usually may cause the failure of some innovation projects (Pellegrino & Savona, 2017). Also, risks, costs, and uncertainties are weight against benefits and incentives that would be gained by the organisation that implements innovation (Chor et al., 2014). Such activities are practical ways used by organisations to analyse the desirability of innovation (Prest & Turvey, 1965).

Several scholars point out the importance of leadership and support in the decision to adopt innovations (Greenhalgh et al., 2004). In particular, this mostly relates to CEO advocacy (Chor et al., 2014). The alignment between innovation and prior organisational goals makes the adoption more likely (Greenhalgh et al., 2004). Some scholars maintain that innovation adoption is more probable when key individuals (e.g., CEO) are willing to support innovation in their social networks (Greenhalgh et al., 2004). Likewise, the organisation must also have the technical capability to evaluate innovation (Boh et al., 2014). To this end, the presence of technical support and expertise, as well as IS infrastructures, are important indicators of an organisation evaluating its readiness for I4.0 (Hameed et al., 2014).

As already mentioned, an organisation must be capable of the successful adoption of innovation. However, not only it needs technical capability but also the expertise to deal with its market environment (Zhang & Hartley, 2018). As such, both the level of competitive pressure and the level of customer interaction are useful indicators for the adoption decision (Priyadarshinee et al., 2017). Several scholars maintain that the level of competitive pressure is an implicit consequence of the accelerated competitive environment, primarily due to the desire to create new products and processes in an improvised manner (Zhang & Hartley, 2018). Subsequently, scholars claim that the level of customer interaction is a critical determinant of the organisational performance; thus, also important for the adoption decision (Manral, 2010).

The geographic location of an organisation also plays a vital role in indicating the status of the adoption decision. Several scholars claim that geographical proximity is a necessary condition in the diffusion of knowledge or innovation (Martinez-Noya & Garcia-Canal, 2017). It is, thus, widely accepted that determining the geographic location of an organisation is a first-order strategic decision of stakeholders (Escuer et al., 2014). On the other hand, the reputation of suppliers is an important indicator at the decision stage. Since I4.0 promises new products and process innovations, potential adopters ensure that during the implementation stage, they would not face the risk of knowledge leakage. Knowledge leakage becomes a potential problem in at least two ways, i.e. (i) when suppliers serve a competitor who puts the organisation at the risk of knowledge spill-over in favour of the competitor, and (ii) when the supplier becomes a potential competitor due to the knowledge spill-over (Martinez-Noya & Garcia-Canal, 2017). Moreover, scholars argue that such risk is higher at locations with weak intellectual property (IP) protection.

3.3. Post-Adoption Stage

The post-adoption stage occurs when a decision unit puts the technology in use (Rogers, 1995). That is, a decision unit, as in an organisation, finally implements the technology and correspondingly evaluates the advantages and disadvantages of technology adoption, which in turn, guides organisations in their decision of whether such adoption should be continued or not. Such action boosts the efficiency of an organisation, given its successful application of new technology in the local context as well as its capability to compete according to strategies and action plans (Oyemomi et al., 2019). This adoption decision, however, is subject to a certain degree of integration depending on the available resources and risk aversion of an organisation (Hameed, 2012). When an implemented technology is perceived to be riskier, an organisation's willingness to continue the adoption may correspondingly diminish.

In the case of the I4.0 adoption, it is a basic necessity to ensure open access to critical technologies, such as IoT, CPS, smart manufacturing, and cloud computing (Priyadarshinee et al., 2017). When organisations have a sense of ownership stake in one or more critical I4.0 technologies, the eventual post-adoption of such technology becomes more attractive. Otherwise, the acquisition of these technologies may potentially delay the I4.0 implementation on the grounds of economic risk barriers, financial leverage, and functionality of service quality offered by the new technology amidst the competition in the supply chain network (Joachim et al., 2018).

Also, the amount of operational cost reduced in the implementation of I4.0 must be deemed reasonable for organisations to continue using the technology (Lee et al., 2015). When representations of cost reduction as in pay-per-usage and reduced facilities are substantial enough to warrant a continued adoption of technology, organisations can be further driven to do so. The same inference can also be drawn for economies of scale (Priyadarshinee et al., 2017) and work simplification (Jeyaraj, 2006).

An organisation that implemented I4.0 is expected to have a system that is adaptive by plug-and-work mechanism (Monostori et al., 2016), autonomous (Letia & Kilyen, 2018), decentralised (Terziyan et al., 2018), dependable (Alguliyev et al., 2018), interoperable (Priyadarshinee et al., 2017), capable of real-time operations (Terziyan et al., 2018), remote monitoring and control (Sung, 2018), resilient (Chang et al., 2016), robust (Alguliyev et al., 2018), capable of handling full information (Sabherwal & King, 1991), flexible (Browne et al., 1984), capable of maintaining data lifecycle (Tao et al., 2018), usable (Priyadarshinee et al., 2017), and with intelligent lots (Li et al., 2012). Given that such capabilities are made possible by critical I4.0 technologies, an organisation is more likely to confirm the continued adoption of such technology, based on trials when its performance meets prior expectations. That is, a positive assessment should be observed with the benefits outweighing the issues arising from the adoption of I4.0

(Miranda et al., 2016). Such issues may include maintainability (Blanchard et al., 1995), multilingualism (Jeyaraj et al., 2006), and exposure to operational risk (Hoffman, 2002). In such a case, the new technology proceeds to be institutionalised and part of the daily operations of the adopting organisation (Rogers, 1995). Otherwise, a probably discontinued adoption, if not withdrawal, of the technology may be decided when an organisation perceives more inhibited changes in the transformation process (Lienert, 2015).

Other strategic activities, such as the formalisation of systems development (Mathiassen & Munk-Madsen, 2007), knowledge transformation (Chor et al., 2014), a culture of change (Lienert, 2015), customer co-creation (Sung, 2018), intense research and development (Chor et al., 2014), and partnership establishment (Priyadarshinee et al., 2017), are also considered as indicators of this post-adoption phase. While the I4.0 adoption continues, it is imperative for organisations to regularly align their goals to a prescribed implementation on the following: (1) required brand and methodology specifications, (2) ideal product and project developments, (3) perceived change in the demands of core tasks, (4), open innovation among organisations and customers, (5) substantial efforts of generating innovative ideas, and (6) strong ties within a network of suppliers. As a result, straightforward transparency among customers and just the involvement of humans (i.e., operators or workers) in the loop may be upheld.

In summary, sets of indicators for each stage are positioned according to relevance as stipulated by a robust guideline. This guideline is streamlined like a conventional decision-making process where actions are preceded by the process of assessment and selection. In the context of the I4.0 implementation, this process is broken down into three segments, that is, perception, decision, and implementation, represented by the three stages of adoption. The pre-adoption stage encompasses indicators relevant to the perception of stakeholders as to the level or status of an organisation's I4.0 technology adoption. This apprehension is influenced by the knowledge and understanding of the involved personage about technologies that fall under the concept of Industry 4.0. This stage also includes the evaluation of the advantages and disadvantages of potentially implementing or rejecting I4.0 technology. The adoption stage includes indicators that discuss the decision-making process undergone by stakeholders in their conjecture for the potential to adopt or reject the technologies highlighted at the previous (pre-adoption) stage. The suitability shapes the final decision regarding the technology in terms of the fit for the organisation's needs and goals. Going from one stage to the next, the scope of the decision-making process becomes more complex. Moreover, at this stage, indicator sets provide a detailed outlook on being able to initially distinguish the capabilities of an innovation that tailor to the organisational needs. The post-adoption stage mainly concerns indicators that aided in confirming the initial evaluation set at previous stages and, thus, provide insights on the likelihood to continue the implemented innovation, or otherwise, end its use when proven to be depreciatory.

3.4. Final note on indicator sets for stages of adoption

In summary, there are 11 indicators at the pre-adoption stage, 14 indicators at the adoption stage, and 37 indicators at the post-adoption stage. Every stage of adoption has a different number of indicators, which signifies its outright position in terms of stage suitability. In terms of a stage, suitability means that indicator sets are assigned to the most appropriate stage where a thorough management dashboard is deemed most necessary. It is also important to emphasise that this paper aims to present a set of indicators for every stage of adoption concerning its function and contextual representation rather than evaluate indicators at each stage quantitively. Some indicators need to be firmly established at a particular stage, so that its implicit representation in succeeding stages may already be covered. As an illustration, take, for example, the following indicators of the pre-adoption stage: the perception of the term Industry 4.0, perceived ease of use, and observability. It is canonical for business stakeholders to be able to initially distinguish the capabilities of innovation before making the adoption decision (i.e., adoption stage) and its eventual implementation (i.e., post-adoption stage). Following this principle, indicators — such as the perception of the term Industry 4.0, perceived ease of use, and observability — are believed to be most suitable for the pre-adoption stage since they represent the knowledge or awareness of innovation as well as the perception of stakeholders. This compels stakeholders to create an effective management dashboard based on such indicators and other strategic data that comes with it at this stage. Furthermore, it is necessary to understand that as stages of adoption progress, the scope of decision-making attributed to stakeholders becomes vast and even more complex due to the implied transfer and continuous management of tasks embedded in each indicator. That is, despite a unique set of indicators in succeeding (i.e., adoption and post-adoption) stages, it is nevertheless suggestive of the continued attention to the indicators of the previous stage.

4. Proposed applications

The applicability of the proposed indicator sets is demonstrated by two case studies of two leading manufacturing firms in the Philippines. Generally, indicators are developed to manage and plan a company's operational performance appropriately. Conversely, there have been several aggregation methods developed to come up with a single score aggregate index present in the extant literature, such as the fuzzy Delphi method (FDM), analytic hierarchy process (AHP), analytic network process (ANP), simple additive weighting method (SAW), decision making trial and evaluation laboratory (DEMATEL), the technique for the order of prioritisation by similarity to ideal solution (TOPSIS), aggregated indices randomisation method (AIRM), etc. In the context of this study, the LWAA operator method was used to arrive at an overall performance index of a firm's status on the I4.0 adoption. Aiming to maintain the generality in the list of indicators, all indicators were assumed to have equal weights, although this assumption may not hold in practice. Assigning weights of all indicators is out of the scope of this work. To assign weights to indicators, firms may adopt a prioritisation process.

The following sections present the two case studies. Each case focuses on firms that have adopted a new form of technology in their production processes.

4.1. Case study 1

The first case study was performed at a premier designer and manufacturer of electronic components for mobile communications and consumer electronics, producing microphones, speakers, and medical hearing devices. The company has been introducing disruptive technologies for over 65 years and is one of the industry leaders at present. Its strong drive for continuous improvement has pushed the firm to acquire and integrate innovative concepts and new forms of technology in its manufacturing processes. For the past two years, it has adopted the concept of IoT in its products to further enhance user experience. Also, it has ongoing plans for the implementation of smart manufacturing in incoming brands. Consequently, it can be argued that the firm has had a proper understanding of I4.0 and its implementation. To demonstrate the application of the proposed innovation stages and actual industry implications, this section presents the results of the evaluation of company A.

For company A, a sample research questionnaire used at the pre-adoption stage is presented in Table 3, further showing the linguistic ratings given by respondents for each indicator on the list. Subse-

Tab. 3. Sample pre-adoption stage questionnaire for company A

Company A						
No.	Indicator	Very Poor (VP)	Poor (P)	Fair (F)	Good (G)	Very Good (VG)
1.	Compatibility					✓
2.	Perceived ease of use				✓	
3.	Perceived usefulness					✓
4.	Flow experience				✓	
5.	Internal information sources				✓	
6.	External information sources				✓	
7.	Observability					✓
8.	Perceived risk			✓		
9.	Perception of the term Industry 4.0					✓
10.	Subjective importance of tasks				✓	
11.	Technological innovativeness					✓

Tab. 4. Sample post-adoption stage questionnaire for company B

Company B						
No.	Indicator	Very Poor (VP)	Poor (P)	Fair (F)	Good (G)	Very Good (VG)
1.	Access to I4.0 technologies					✓
2.	Adaptivity by plug-and-work				✓	
3.	Auditability				✓	
4.	Culture of change					✓
5.	Customer co-creation				✓	
6.	Data lifecycle				✓	
7.	Decentralisation					✓
8.	Degree of autonomy				✓	
9.	Degree of integration				✓	
10.	Dependability					✓
11.	Economies of scale					✓
12.	Financial leverage					✓
13.	Formalisation of systems development					✓
14.	The functionality of service quality					✓
15.	Human in/outside the loop					✓
16.	Information intensity					✓
17.	Intelligent lots				✓	
18.	Interoperability					✓
19.	Knowledge transformation			✓		
20.	Machine flexibility			✓		
21.	Maintainability					✓
22.	Manager risk tolerance					✓
23.	Multilingualism					✓
24.	Operational risk					✓
25.	Organisational efficiency					✓
26.	Organisational performance					✓
27.	Partnerships					✓
28.	Performing trial for the organisation of innovation					✓
29.	Real-time capability				✓	
30.	Reduced operational cost				✓	
31.	Remote monitoring and control capability				✓	
32.	Research & development intensity		✓			
33.	Resiliency					✓
34.	Supply chain integration					✓
35.	System robustness					✓
36.	Usability					✓
37.	Work simplification					✓

quently, based on Xu (2006), the respondent answers were coded into five extended discrete linguistic labels expressed in equation (2). Then, to come up with a single score aggregate index for each stage, equation (3) was used. For the pre-adoption stage, using the proposed procedure presented in Section 3.3, company A attained an overall score of 1.364, signifying a good performance. Meanwhile, the adoption and post-adoption stages achieved good and fair scores of 1.643 and 0.784, respectively. These ratings imply that initiatives performed by the firm are aligned with the performance of each indicator concerning the implementation of I4.0 technologies. Since company A has a fair adoption performance, it needs to devise a holistic strategy to enhance its performance. Table 3 also provides insights into the performance of company A in terms of each indicator. Of the 11 indicators, the indicator of perceived risk has the lowest performance value, which implies that company A has limited risk assessment efforts in the adoption of I4.0 technologies. Thus, a thorough assessment of risks in various sources must be implemented to improve its pre-adoption status.

Furthermore, the evaluation provides insights into areas of improvement for the company A. By dichotomising each indicator, company A may adopt insights into its decision-making process, resource allocation decisions, and strategy formulation. However, these results must be considered with caution as some limitations in the evaluation process exist. First, just for the sake of demonstrating the applicability of the proposed indicator system, the case study only focuses on a small group of decision-makers who performed the linguistic evaluation process.For a more rigid application, an evaluation must be carried out holistically and involve a well-represented group of decision-makers from among all company stakeholders. Second, the evaluation is rough, as more quantifiable metrics were not determined for each indicator. Metrics could provide more meaningful and realistic measurements of indicators, which would provide a clear understanding of performance in terms of the I4.0 adoption. Third, coming up with a single-valued index, weights of indicators are considered equal. It is straightforward to note that each indicator has a varying degree of importance to a stage of the I4.0 adoption. Thus, having indicators of equal weights is just an oversimplification of complex real-life decision-making. Stakeholders may collectively assign a weight for each indicator based on its importance for an I4.0 adoption stage.

4.2. Case study 2

The second case study focused on a leading supplier of automotive seating solutions and electrical distribution systems and architectures. Products of this company have consistently delivered an elevated automotive experience for the end-users. As a global business that has been in the market for more than a century, it has continually achieved excellence by rigorously adapting to new technologies. To date, it has adopted the concept of IoT and smart manufacturing in its production processes to achieve a smoother flow of materials and workforce from the dock to dock. The extensive experience of the company in acquiring and implementing innovative strategies makes it another suitable source for the verification of the practical relevance of indicator sets.

Ratings issued by company B are presented in Table 4. Using the same procedure as with company A, the respondent's answers were coded as in equation (2). For the computation of the overall performance, equation (3) was used. As for the post-adoption stage, the overall index had a value of 1.541, which denoted a good implementation performance. Thus, indicators of this stage of the I4.0 implementation are well-evident at the firm. However, similar implications and precautions of the results, as discussed in the case study 1, are also applicable in this case. For brevity, these discussions are not presented.

Conclusions

While innovation strategies in globalisation domains have been modelled after different stages of adoption, unfortunately, the implementation of Industry 4.0 has not been established in the same way despite being under the agenda of innovation. Due to the multi-phase and multi-dimensional nature of innovations in general, it is imperative to put more emphasis on various stages of adoption, so that dominant issues arising distinctly from each stage could be addressed more responsively by firms using programmes and initiatives. Furthermore, providing such a holistic approach embedded in the innovation process can potentially prevent haphazard implementation, poor resource allocation, and a myopic view of I4.0. Among other approaches in the holistic evaluation of the innovation process, the development of indicator sets is deemed by stakeholders a crucial step towards effective decision-making, resource allocation decisions, and strategy and policy formulation. Quantifiable sets of indicators allow managers and decision-makers to keep track of their I4.0 performance and strategically plan and direct initiatives to progress more efficiently and effectively.

Thus, this work intends to close two critical gaps in the literature: (a) to treat I4.0 as the innovation process that has specific adoption stages, and (b) to develop an indicator set for each stage. After a comprehensive review of related literature, 62 indicators are extracted: 11 for the pre-adoption stage, 14 for the adoption stage, and the remaining 37 for the post-adoption stage. The distribution of indicators according to the adoption stage was based on its operational description and its relations to the innovation process. Indicators at each I4.0 stage were intended to describe the status of an organisation in its path towards the I4.0 adoption as well as serve as dashboards in gauging the organisation's direction and its speed of implementation. Note that the status that can be generated from the indicators is the performance of an organisation in discrete time rather than continuous. Thus, these proposed indicators provide a picture of an organisation at a particular stage and specific time.

The pre-adoption indicators are mostly generated by the perception of potential adopters except for one indicator (i.e., technological innovativeness), which depends primarily on the attitude while adoption indicators relate to the evaluation activities of potential adopters concerning their financial, technical, and organisational capabilities. Note that the majority of the identified indicators belong to the post-adoption stage. This finding implies that this stage critically shapes the decision-makers in finally implementing the technology and evaluating the advantages and disadvantages of adoption. Furthermore, indicators in this stage dictate whether the adoption is continued or not, depending on how the desirability of benefits outweighs the severity of risks, or vice-versa.

With the proposed I4.0 indicators, some possible applications can be described. First, indicators may help organisations establish strategic plans, both short-term and long-term. At the pre-adoption and adoption stages, stakeholders may implement organisation-wide information campaigns, so that all levels of the organisation may better understand the role of technologies integrated into I4.0 as well as its capability to bank on the empowerment of organisations in identifying opportunities for the I4.0 implementation. At the post-adoption stage, resources can be allocated appropriately so that critical indicators can be sufficiently supported. Second, indicators promote a platform for performance evaluation. With the use of these indicators at various stages, managers and decision-makers can reflect the organisation's performance and eventually produce inputs in planning initiatives and strategies. Additionally, performance evaluation can be served as inputs in employee reward systems. Third, establishing indicators may leave open areas of improvement that must be addressed to adopt I4.0 successfully. On the supply side, such indicators may serve as metrics for hotspots to inform the developers of I4.0 (e.g., CPS, IoT, etc.) about the ease-of-adoption of I4.0. For instance, if most potential adopters have a high score for one indicator, developers may modify the technologies used in I4.0, so that they become manageable, hence, increasing the chance of adoption. Finally, the proposed I4.0 indicators can serve as inputs to balanced scorecards and performance dashboards. This application is particularly relevant to the post-adoption stage, where managers can monitor the performance of their organisation in light of these indicators.

While two case studies were presented in this work to shed more light on the use of I4.0 indicators, such demonstration has some limitations. First, performance ratings are desirable from more involved focus-group discussions at various organisational levels. In the case studies, middle-managers were only asked to provide ratings that may not reflect the perspectives of upper management and first-line management. Thus, involving the perspectives of different organisational levels may provide a more accurate reflection of organisational performance. Second, although the indicators project quantifiable measurement concepts, there is room to entertain the idea that defining each indicator with finer metrics would provide higher resolutions of organisational performance in terms of I4.0. Thus, managers and decision-makers could establish metrics for each indicator relevant to a specific industry. Third, in the case studies, the assumption that I4.0 indicators have equal priority weights does not reflect real-life conditions. It is plausible to note that I4.0 indicators play varying roles to a certain degree so that the establishment of priority weights for each indicator is much desired. Managers, with the aid of analysts, may adopt any suitable prioritisation methods such as simple additive weighting (SAW), analytic hierarchy process (AHP), best-worst method (BWM), etc. With the implementation of these methods, the role of each indicator in I4.0 adoption may be better highlighted.

Finally, an indicator system that contains a rigorous framework for a composite index can be implemented by managers and decision-makers. Indicator systems can be structured in a hierarchy to generate a composite index that describes the overall performance of an organisation at a particular adoption stage. This information regarding the overall performance provides a macro view on the status of the I4.0 adoption stage, which can be used by organisations for monitoring and comparison with other market players.

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Building production management practice in the construction industry in Nigeria

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ABSTRACT
Growing demands for building projects result from economic development. The building industry is dynamic and multifaceted. Efficient and effective practice of building production management (BPM) is required to successfully execute projects and achieve project goals upon completion as well as functionality aims for the lifespan of a building. This research aims to determine factors that influence the BPM practice in the Nigerian construction industry, particularly; during the project execution phase. A cross-sectional survey used; a questionnaire to identify 73 factors, which were grouped into 12 categories and assessed. A purposive sampling technique was used to identify 20 construction organisations specialising in building production management in Lagos, Nigeria. 114 questionnaires were distributed to the pool of stakeholders, which included 31 clients, 34 consultants and 49 contractors of current and past building production projects carried out by the selected firms in Lagos. The research used a selection of statistical tools for SPSS v.23, including the chi-square test, the Kruskal-Wallis test and Kendall's coefficient of concordance. The obtained result revealed the factors that mostly influence the BPM practice namely, architectural drawings, the construction programme document, the work breakdown structure, the adequacy of communication and coordination between the parties, the adequacy of raw materials and equipment, the availability of the competent team, the implementation of the safety management system, regular maintenance of project equipment, clear and timely inspections, the availability of funds as planned throughout the project duration, the availability of skilled personnel, and the aesthetics of the completed work. The research resulted in the development of the BPM implementation framework and recommendations for the improvement of the BPM practice in Nigeria.

KEY WORDS
building production management, practice, Nigerian construction industry, theory, critical success factors

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Introduction

Increasing client expectations, high demands related to construction time and cost, and the growing complexity of construction methods have made the building industry dynamic and multifaceted. As stated by Olanipekun, Aje and Adedokun (2014), the construction industry is diverse because construction professionals come together from different backgrounds, with varied training and experience to deliver common project goals. According to Odusami, Oyediran and Oseni (2007), construction companies must develop plans to survive in the competitive envi-

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ronment filled with client demands, and be competent in identifying those client requirements for contractors that aim for higher quality services. The Nigerian construction industry plays a vital role in economic development (Ugwu & Attah, 2016), which in turn increases the demand for building projects. According to Nwachukwu and Emoh (2011), the building development sector has proven to be the backbone of national economic growth; therefore, it is imperative that building projects are managed efficiently and effectively. This indicates the need for effective and efficient practice of building production management (BPM) in the building sector.

According to Henrich and Koskela (2006), production management methods can be responsible for many construction project failures. In most construction firms, a high rate of business failure results from the lack of skills and knowledge (Kanyago, Shukla & Kibachia, 2017) as well as the insufficient understanding among stakeholders of duties and responsibilities ascribed to industry professionals or experts managing building projects in Nigeria (Anyanwu, 2013). These issues and general negligence may cause; project delays and budget overruns, economically unviable design and solutions, inadequate specifications, poor workmanship, and rework.

Ineffective building production management (BPM) can negatively impact on the national economy. According to Osuizugbo (2020), ineffective BPM has negative implications on construction companies as well as the economy, and can only result in rework, budget overruns, project delays, premature project termination, poor workmanship and building failure/collapse. Aliyu, Adamu, Abdu and Singhry (2015) pointed out that ineffective work was the leading cause of poor project performance in the construction sector. Furthermore, the impact of the construction industry on the economy is directly associated with project performance. Ineffective BPM practice may also damage the reputation of the project team. According to Odediran et al. (2012), ineffective project management affects the company's competitive position in the market. Osuizugbo (2020) defined ineffective BPM as used inefficient operating methods, competence deficiencies among management and construction workers; or poor design and specifications, which lead to extra work. Most Nigerian cases of BPM are executed by unqualified people, such as artisans, craftsmen and technicians, who have no knowledge of technological or construction processes including the construction phase (Anyanwu, 2013). Ineffective BPM obstructs innovation, creativity, and the sector's growth (Osuizugbo, 2020). According to Anyanwu (2013), ineffective BPM wastes time, money, material and human resources, and generates an immense loss to the economy. Consequently, there is a pressing need to call for a solution because, construction failures, abandoned and collapsing building impede the development, economy and investment (Nwachukwu & Emoh, 2011).

This study emerged from the problems faced by building production management. The research aims to assess the local practice of building production management (BPM) with the view to improve the state of play of the Nigerian construction industry. To achieve this aim, the study identified and evaluated factors that affect the practice of building production management in Nigeria. Although this study applies specifically to the Nigerian construction industry, the same method could be used to in other countries that face issues of ineffective building production management.

1. Literature review

1.1. Nigerian construction industry

Historically, the construction industry has always been related to the process of industrialisation and development (Lopes, Oliveira & Abreu, 2011). The productivity of the construction industry in Nigeria, according to Aniekwu, Igboanugo and Onifade (2015), is very low compared with other industries, which is the result of a continuously used traditional project delivery method, which fails to effectively encourage the integration between design and construction, as well as the coordination and communication between participants of the construction industry. The Infrastructure Client Group (2015) states that; traditional methods are burdened with significant shortcomings that affect ways for the preparation and handling of construction projects. The industry consists of both the public and private sectors, but it is mostly private, while activities includes the procurement of goods and services, and the execution of various projects, such as building, civil engineering, power and energy, etc. (Okoye, 2016). The construction industry is the means, through which nations realises their potential goals for urban and rural development (Kanyago et al., 2017), while its activities and products are an essential part of the national economy and industrial development in developing countries, one of which is Nigeria (Okoye, 2016).

Globally, the construction industry accounts for 6-9% of the Gross Domestic Product (GDP) of many countries (Kanyago et al., 2017). In Nigeria, the industry accounts for a substantial percentage of the Gross National Product (GNP) and constitutes almost half of the total public spending (Aniekwu et al., 2015). The relationship between the construction sector and the actual GDP was found to be significantly and strongly positive (Okoye, 2016). The Nigerian construction industry mainly consists of small and medium construction firms, with very few large multinationals. Most construction firms have less than ten employees, while several multinationals have hundreds (Jimoh, 2012). According to Okoye (2016), construction workers in Nigeria are hardly literate and poorly paid, having to work long hours under poor workplace conditions, which is often dangerous manual work.

The Nigerian construction industry plays an essential role in the national economy. Up to now, it has been battling with serious issues and challenges, such as cost overruns, project delays, economically unviable design, poor workmanship, rework, inadequate specifications, impracticable and uncontrolled schedules, deficient detailing, misunderstandings among project team members, and abandoned and uncompleted public and private building projects. These days, it is extremely common to see a collapsing building. Such frequent incidents have shaped a negative public opinion about the industry. Consequently, there is a pressing need to improve the BPM practice in the country.

1.2. Building Production Management (BPM)

BPM has been defined as the management of building production information, equipment, materials, labour and other resources that are used in the physical realisation of a building project, at the same time adhering to building codes and contractual conditions (Osuizugbo, 2020). It follows that BPM is the overall management of building production on site. According to the Nigerian Institute of Building (NIOB) (2002), in Nigeria, BPM is perceived as the main role/scope of professional service rendered by builders to clients in any building project. The scope of services under BPM includes the analysis of building production information, construction planning and the management of the production process on site.

Building production information includes architectural drawings, electrical and mechanical drawings, specification documents and structural drawings (Osuizugbo, 2018, 2019). Various documents are required during the phase of construction planning and the process of site production management. These BPM documents include the project health and safety plan, the construction programme and the project quality management plan (Okoye & Ngwu, 2015). Studies conducted by Okoye and Ngwu (2015) reported a low level of awareness and extremely low use of these documents, which indicates that the documents are not considered important in building production management. Other BPM documents, which are crucial for project performance improvement include the construction methodology, the early warning system chart and the information requirement schedule (NIOB, 2002).

During the phase of construction planning and site production management, project management tools or techniques are also important to BPM practice. Studies described several project management tools or techniques, including Projects in Controlled Environments (PRINCE/PRINCE2), in-house project management methods, cost-benefit analysis (CBA), decision analysis (DA), the buildability and maintainability analysis, in-house decision-making techniques, the programme evaluation & review technique, the project sensitivity analysis, the graphical evaluation & review technique, Line of Balance, the critical path method (CPM), work breakdown structure (WBS), life-cycle cost analysis (LCCA), the probability analysis (PA), in-house risk assessment tools and Gantt bar chart, etc. (Haron et al., 2017; Ugwu & Attah, 2016; Osuizugbo, 2018). Most of these project management tools and techniques are rarely used in the construction sector. For example, Haron et al. (2017) found that CBA, Gantt bar chart, and CPM are the most widely applied project management tools and techniques in the construction sector. The studies of Ugwu and Attah (2016) also found that the critical path method (CPM) was the most important project management technique that influences the management of construction projects.

Virtually all business activities are housed in a structure, which is generally referred to as a building. Its production attracts professionals and non-professionals and is considered to be complete when the project is handed over to the client (Nwachukwu & Emoh, 2011). As one of the most valuable assets of humankind, it needs to be properly structured (Osuizugbo, 2018). According to Ugwu and Attah (2016), construction projects in Nigeria are expensive; thus, it is of utmost importance to focus on construction practice and the best methods. Most times, project managers prepare a work programme without the input of actual workers, often starting tasks that cannot be completed (Infrastructure Client Group, 2015). The Infrastructure Client Group (2015) stated that, about

50% of works started on construction sites could not be finished as planned, which resulted in up to 50% of construction man-hours to be unproductive.

The solution to building failure, abandonment, building collapse, and project success; depends on efficient and effective BPM practice. The BPM process begins with the analysis of design information. The application of BPM practice is a well-organised approach to building production, which helps improve the capabilities of the building industry, thereby delivering and achieving success at the end of the project. When BPM is practised efficiently and effectively, it certainly results in massive tangible benefits received during the three main phases of the building process, which include the design, planning and production processes, which are the key focus of BPM. Professionalism plays a crucial role in the BPM practice as it determines the management of resources invested in the project for the benefits of clients.

1.3. Theoretical framework for BPM

The description of the production theory based on the economic principle mainly focused on the relationship between input and output. Osuizugbo (2020) outlined a new theoretical foundation of construction production, which rested on pillars of transformation, flow, and value generation. As stated by de Valence (2012), these three theories should be managed concurrently. Views regarding the BPM transformation and flow focused on different aspects of building production management. According to Koskela (1999), the transformation concept is based on the value-adding tasks with the main focus of transformation view placed on defining the task to be done; and achieving it professionally, whereas the flow concept is based on non-value adding activities, with the focus on the elimination of waste from flow processes.

Transformation theory

In the construction system, production takes inputs in the form of labour, materials, finance, information, plants and equipment, and converts them into the expected services and products, otherwise known as outputs. The principles of a classical transformation include (i) the division of production into smaller controllable sub-processes and further into tasks, then making available all the inputs required for a particular work section and then allocating these tasks to workers; (ii) the reduction of the project cost by minimising each cost of the sub process; and (iii) linking of the input value of a process with the output value (Gao, 2013). In practice, the value of a finished building can be increased using skilled labour, better materials and effective task management (Gao, 2013). This theory is particularly relevant to BPM because it explains the need to define works required to deliver a construction project, which helps to avoid unnecessary efforts.

Flow theory

According to Koskela (1999), flow processes include inspection, waiting, and moving, which represent waste (non-transformation activities) in production. As outlined by Gao (2013), the principles behind flow processes include (i) the reduction of activities that add no value; (ii) the reduction of lead time and variability; and (iii) simplicity, increased flexibility and transparency. The flow theory seeks to manage and continuously improve production, by making sure that unnecessary works are reduced to the barest minimum (Koskela, 1999). The sources of activities that add no value (waste) are (i) the production system structure; (ii) the production control style; and (iii) the characteristic nature of various phases in production, such as design, control and advancement of production (Gao, 2013).

Value generation

Value creation is the utmost concern in production management. It is a process whereby value for the client is formed by way of satisfaction of needs and eliminating value loss (i.e. with the help of value management) (Gao, 2013).

1.4. Conceptual framework

This study presented stages of the construction process, where the BPM practice can be implemented as presented in Table 1. The BPM framework aimed at improving the three main phases of the construction process. With the help of this framework, construction companies or developers and prospective clients are expected to achieve project objectives, increase efficiency and quality, and reduce time, costs and delays. Table 1 shows the summary of a typical BPM implementation framework with each phase in the construction process finalised by a decision (NIOB, 2002).

1.5. BPM experts

In the building industry, it is especially important to identify stakeholders and understand the roles they play in a project delivery. Failure to identify fraudulent stakeholders in the execution of a particular service can negatively influence the entire project. “It is not about knowing how to read an architectural or struc-

Tab. 1. BPM implementation framework

Phase	Work section	Tasks to be completed	Directly involved people	Work result	Decision to be reached
Design process	Buildability and maintainability analysis	1. Production information analysis (such as drawings, specifications, schedules, etc.); 2. Note-taking on problems such as omissions, inconsistencies and access for maintenance that could severely affect the future maintenance, efficient and economical building production; 3. Report documentation and advice on an efficient, economical and effective solution for building production; 4. Presentation of the buildability and maintainability analysis report to the project manager or client	design team, builder, contractor, project manager and client	design that facilitates the ease of construction and maintenance; or simply design a building that is production-friendly	solutions regarding the production information
Planning process	Construction planning	1. Preparation of the sequence of site operations; 2. Preparation and/or examination and review of the construction methodology document; 3. Preparation and/or examination and review of the construction programme document; 4. Preparation and/or examination and review of the project quality management plan document; 5. Preparation and/or examination and review of the project health and safety plan document; 6. Preparation and/or examination and review of the early warning system chart document; 7. Preparation and/or examination and review of the information requirement schedule document; 8. Preparation, examination and review of the project site organisational structure noting the conforming competence or otherwise; 9. Preparation of the construction planning report; 10. Presentation of the construction planning report to the project coordinator/manager or client; 11. Arrangement of workforce and tools, preparation of the access road to the site, hoarding installation, erection of temporary shops and huts, and tidying up the site	contractor, builder, project manager, and client	site prepared and ready for actual construction activities	readiness for the execution of the building project
Production process	Managing site production process	1. Delivery of materials to the site; 2. Setting out the building; 3. Site meetings, accounts, and financial control; 4. Engagement of resident builder(s) in the day-to-day management of the site production process; 5. Enforcement (appraising where necessary) of the use of all production management documents (PMDs) on and off the site; 6. Evaluation of workmanship services provided by artisans; 7. Suggestion of solutions to site difficulties and technical problems; 8. Preparation of BPM reports to be included in the periodic project reports	contractor, builder, project manager, and client	completed building	alternatives in the case the production or operations cannot proceed as planned
	Completion	1. Technical inspection upon completion; 2. Correction of errors, defects, and shortcomings; 3. Final technical inspection	design team, contractor, builder, project manager, and client	completed building, which, in the case of acceptance, is handed over to the client	acceptance of the quality of the building works carried out by the project team

tural drawing or having money to go into real estate and property development that makes one a builder or an engineer, it is all about having the required skill and academic discipline to marry the profession" (Osuizugbo, 2018). According to Osuizugbo (2018), evidence has shown that in the Nigerian construction industry, people perceive building and construction works as a quick means of making money; thus any lawyer, microbiologist, political scientist or even a trader can enter construction and engineering professions undisturbed. People without appropriate training can dabble in the field of engineering and construction uncontrolled due to the lack of regulation regarding the practice in the Nigerian construction sector. Construction management requires suitable skills and techniques, including sound and adequate management skills (Ugwu & Attah, 2016).

The scope of services/roles of professionals in the building industry has been the interest of many researchers. According to the study by Jimoh (2012), an architect is the one that determines the concept, the size and the layout of the building, while a builder is practitioner who is in charge of the production management right from site acquisition to handover, displaying good site management practice, which is vital for efficiency, cost effectiveness and control of the project.

According to Anyanwu (2013), architects and engineers prepare the designs of a building, while the execution is the role of professional builders, project managers and technical support workers. Anyanwu (2013) went further by stating that professional builders were the professionals of the physical construction works, and the role of a builder in project delivery was to produce a building by undertaking on-site activities, translating designs, drawings, schedules and specifications into a physical structure. Furthermore, builder uses production management skills, and essential resources, such as funds, labour, materials, and machines, to execute the project; a builder's skill in building production management is the core professional contribution to construction projects. According to Olanipekun et al. (2014), the following are unique functions of professional builders: preparing the buildability and maintainability analysis report, making the project quality management plan, devising the project health and safety plan, drafting the construction programme of works, managing the construction process and specifying materials and workmanship.

According to Osuizugbo (2018), in the building construction industry, engineers undertake calculations and analyses to produce a design solution; in other words, just like architects, engineers produce the design solution of a building project. Osuizugbo (2018) went further to described builders as professionals that have an analytical mind, by virtue of their training to organise and coordinate the activities of the tradesmen, subcontractors, and suppliers as well as to manage the entire building production process from the beginning to handover, with a view of ensuring that the project is completed on time, within the cost, and to specify the quality standard by utilising the most optimal construction methodology, also including other unique roles attributed to builders in the building project delivery. According to Bamisile (2004), building production management is the main role of professional builders; and in addition, builders have other major consultancy services. These consultancy services are shown in Fig. 1.

The role of a project manager necessitates for a technical expert to take charge of the construction site and control activities of the project execution process (Nwachukwu & Emoh, 2011), which are obviously some of the attributes of a professional builder. Hence, based on the literature findings, this study concluded that professional builders are BPM experts. In other words, professional builders (technical experts) are the project managers that are well experienced to act as BPM experts.

1.6. Critical success factors

A criterion is referred to as a benchmark or standard, by which something is judged or decided (Frefer et al., 2018). Project success criteria, according to Susil, Warnakulasuriya and Arachchige (2016), mean the measure, by which failure or success of a project is determined. According to Frefer et al. (2018), project success is classified into two groups, namely, macro and micro project success; the macro project success reflects the initial project concept, and when achieved, the project is considered successful, whereas micro project success considers project achievement in smaller unit levels. Contractors and clients view project success from the micro viewpoint, whereas stakeholders and users view project success from the macro viewpoint (Homthong & Moungnoi, 2016). The construction project success is achieved when investors meet their requirements individually and collectively (Takim & Akintoye, 2002); and the best criterion for project success is when the user, project manager and other stakeholders met all their prospects (Frefer et al., 2018). To improve the chances of building project success and reduce the possible failures, the performance

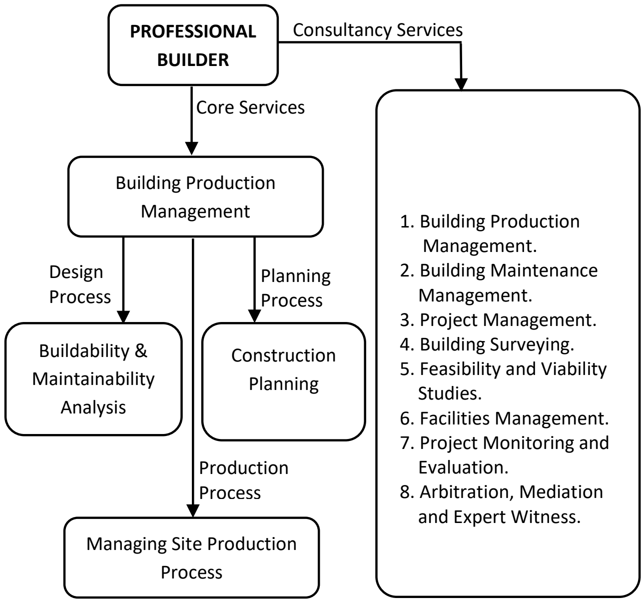

Fig. 1. Summary of professional builder functions in building project delivery
Source: (NIOB, 2020).

criteria for BPM practices should be properly and carefully identified, measured, and checked.

It has been observed that time, cost, quality, health and safety, environment, productivity, risk management, human resource and client satisfaction, among others, are dominant critical success factors reported by construction projects (Omer, 2017; Bryde & Robinson, 2005; Ramlee et al., 2016; Takim & Akintoye, 2002; Bahia & de Farias Filho, 2010; Al-Tmeemy, Abdul-Rahman & Harun, 2010; Koelmans, 2004; Gunathilaka, Tuuli & Dainty, 2013; Frefer et al., 2018; Homthong & Moungnoi, 2016; Gomesa & Romao, 2016; Toor & Ogunlana, 2010; Enshassi, Mohamed & Abushaban, 2009; Mukhtar & Amirudin, 2016). Studies by Homthong and Moungnoi (2016) revealed the most critical success factors influencing project success to include the competence of project participants, the durability of the completed work, the relationship between project participants, positive attitude of employees, effective quality assurance system in the organisation, quality of works to match standards, the relationship between an employee and a supervisor, competent supervisors and regular maintenance of equipment for the project. Haron et al. (2017) identified top five critical success factors that influence the project success to include competency of the project team, customer satisfaction, realistic cost and time estimation, effective planning and controlling and financial attributes.

According to Frefer et al. (2018), project success has two major components, which include issues related to the project and issues related to the client. Traditionally, time, cost, and quality, which are often referred to as the iron-triangle in the literature, are used as project success criteria. According to Homthong and Moungnoi (2016), this so-called iron-triangle has proved to be inadequate for measuring project performance, and the performance indicators are related to many dimensions, such as health, safety, environment, human resource development, client satisfaction, productivity, risk, contract and administration, profitability, and business efficiency. Also, according to Frefer et al. (2018), the traditional project success criteria, which include cost, time and quality, are no longer adequate to measure the success of the project since project success is more complex, and means different things to different stakeholders. According to Aniekwu et al. (2015), consistently low levels of performance are the result of the fragmented nature of the construction process and the distinct separation of industry professions, as well as the lack of concurrency, poor communication, institutional barriers, the lack of trust, ad-hoc problem-solving approach and team work between the client, design or construction team as well as other factors.

The major criteria used in this study to evaluate the BPM performance are time, cost, quality, health and safety, environment, productivity, risk management, human resources, and client satisfaction, as shown in Table 2. Fig. 2 explains the two major components of project success, as described earlier.

Tab. 2. Major project performance criteria summarised from following the reviewed literature

Research (author)	Critical success factors								
	Time	Cost	Quality	Health and Safety	Environment	Productivity	Risk Management	Human Resource	Client Satisfaction
Ramlee et al. (2016)	√	√	√	√	√				√
Takim and Akintoye (2002)	√	√				√			
Koelmans (2004)	√	√	√	√	√		√		√
Gunathilaka et al. (2013)	√	√	√			√			√
Frefer et al. (2018)	√	√	√	√	√	√			√
Homthong and Moungnoi (2016)	√	√	√	√	√	√	√	√	√
Enshassi et al. (2009)	√	√	√	√	√	√		√	√

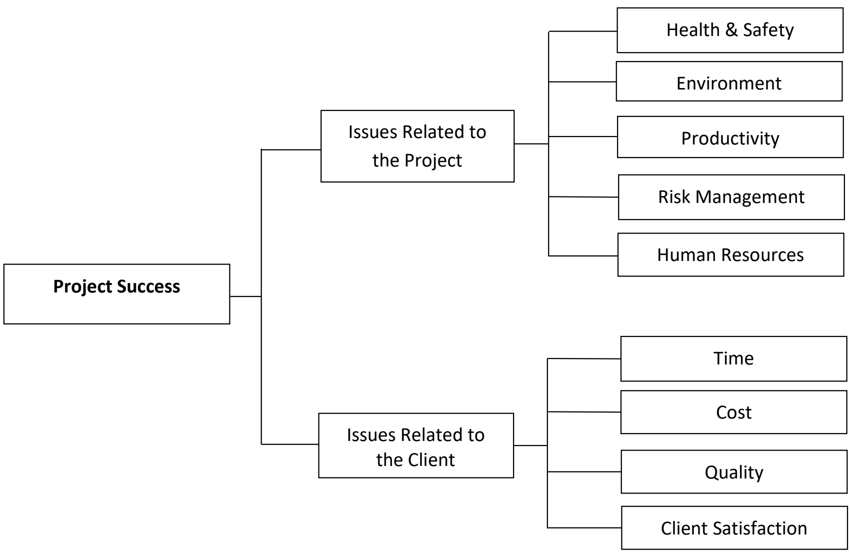

Fig. 2. Components of project success

2. Research method

This research used a field survey method to reveal the BPM practice in the Nigerian construction industry. The list of building production information (e.g. architectural drawings), building production management documents (e.g. the construction programme document), project management techniques/tools (e.g. the critical path method) and critical success factors (e.g. time and cost), which were identified in the literature, were used to design a questionnaire that served as the research instrument to achieve the aim of the study. The questionnaire survey was used to discern the attitude of industry stakeholders. Three groups of stakeholders of the Nigerian construction industry were invited to participate in this study, including clients, consultants, and contractors. A pilot study was conducted to show the accuracy and comprehensiveness of the instrument before distributing it to the participants. The reliability of multiple Likert scale questions was measured using the Cronbach's alpha. Using SPSS version 23, the value of the Cronbach's alpha (α) was 0.959, which indicated a high level of internal consistency for the scale and was considered reliable.

2.1. Study area

The research was carried out in the Lagos state, which is economically significant in Nigeria. The Lagos state has a high volume of building construction activities as well as a large concentration of building contractors of various categories and sizes. The state was also chosen because of frequently collapsing of buildings.

2.2. Data collection

The purposive sampling technique was used in the study to identify the representative sample for the distribution of the questionnaire. The sampling technique is a non-probability method, which is based on the characteristics of the study population. Using a 5-point Likert scale, where No extent = 1, Moderate extent = 2, Medium extent = 3, Large extent = 4 and Very large extent = 5, the participants were asked to indicate the extent of use of each variables, namely, building production information, production management documents, and project management techniques/tools. To determine the level of importance attached to critical success factors, respondents were also presented with a 5-point Likert scale, where Least important = 1, Slightly important = 2, Moderate important = 3, Very important = 4 and Utmost important = 5. Table 3 shows the breakdown of survey responses.

Tab. 3. Questionnaire responses

S/NO	Respondent Groups	Distributed questionnaire	Returned questionnaire	Response rate (%)
1	Clients	31	23	74.2
2	Consultants	34	27	79.4
3	Contractors	49	37	75.5
4	Total	114	87	76.3

2.3. Method of the analysis

The study adopted the following for analyses: Frequency, Percentage, Mean, the Kruskal-Wallis Test and Kendall's Coefficient of Concordance. The analysis used the Statistical Package of Social Sciences (SPSS) v. 23. The frequency analytical tool was used to indicate the proportion of the respondent's characteristics while the percentage tool helped to simplify the proportion of the respondents in the study for better interpretation. The statistical mean was used to show the ranking given by respondents to different variables used in determining the extent of use of building production information, production management documents and project management techniques/tools practices. The Kruskal-Wallis inferential tool was used to determine if there was a significant difference among the clients, contractors and consultants on their ranking of the factors that independently measured the extent of use of building production information, production management documents and project management techniques/tools practices. Also, Kendall's statistical tool was used to test the agreement on the rankings given by BPM stakeholders to factors that influence the Building Production Management.

3. Analysis and results

This section presented the results and analysis of factors that influence the building production management (BPM) practice in Nigeria. The section also presents the demographic information on survey participants.

Tab. 4. Analysis of respondent demographics

Background information	Frequency	Percentage (%)
Professional Background of a Respondent		
Architect	18	20.7
Quantity Surveyor	16	18.4
Builder	27	31.0
Civil Engineer	22	25.3
Mechanical Engineer	1	1.1
Electrical Engineer	1	1.1
Others	2	2.3
Total	87	100.0
Highest Academic Qualification Attained		
HND	40	46.0
B.Sc./B.Tech.	28	32.2
PGD	1	1.1
M.SC	18	20.7
Total	87	100.0
Years of Working Experience in Construction		
Less than 5 years	16	18.4
5 – 10 years	36	41.4
11 – 15 years	20	23.0
16 – 20 years	10	11.5
21 – 25 years	3	3.4
26 – 30 years	1	1.1
31 years and above	1	1.1
Total	87	100.0
Type of Building		
Commercial	33	37.9
Residential	39	44.8
Religion	4	4.6
Office	9	10.3
Others	2	2.3
Total	87	100.0

The respondent background information is summarised and presented in Table 4. As shown in Table 4, 20.7% of the respondents were architects, 25.3% - civil engineers, and builders were the largest group of respondents with 31.0%. In addition, almost half or 46.0% of the respondents were HND holders and 32.2% had B.Sc./B.Tech. Furthermore, 81.6% of participants had from five to more than 31 years of experience in the field of construction, demonstrating adequate competency among respondents to participate in the study. According to Table 4, the majority of participants (44.8%) were involved in the construction of residential buildings.

To measure the extent of use of variables for building production information, production management documents and project management techniques/tools that are generally used in a construction project, respondents were asked to indicate the extent of use of twenty-eight research variables retrieved from the literature and grouped into three categories, namely, building production information, production management documents and project management techniques/tools. Table 5 shows the mean and chi-square values for 28 research variables, which had the mean between 3.01 to 3.80, with about 19 variables averaging between 2.11 to 2.90 and a 1.40. These results indicate that the mean responses to these questions were moderately important, slightly important, and least important, respectively. The Kruskal-Wallis test was run using SPSS v. 23 to determine the association between the variables. The result given in Table 5 showed a weak association and most of the variables were not statistically significant (p>0.05). The result in Table 5 also revealed a statistically significant difference in the mean score of the Programme Evaluation & Review Technique and the Decision Analysis across three groups of respondents. This means that the use of most of the variables depends on the nature of projects. The results also indicate that most of the variables for building production information, production management documents and project management techniques/tools are not used in project execution.

Using a comprehensive literature review, a total of forty-five critical success factors for construction project execution were identified and grouped into nine categories. The survey participants were asked to indicate the level of importance (Table 6) for each critical success factor. The Kruskal-Wallis test was also run using SPSS v. 23 to determine the association between various critical success factors. The results given in Table 6 revealed a weak association between the factors, which were statistically insignificant (p>0.05). It also showed a statistically significant difference in the mean score of some of the factors. This means that the participants did not focus on project performance criteria that could actually contribute to project success. Table 6 also shows the mean and chi-square values for each project performance factor. Forty-five project performance factors had a mean average between 4.00 to 4.13, which means that the mean responses to these questions were very important, excluding 37 factors, which had the mean values of 3.38 to 3.99, indicating moderate importance.

3.1. Significant testing for the hypothesis

The study used Kendall's statistical tool to test an agreement on the rankings given by BPM stakeholders to factors that influence building production management. Thus, Kendall's coefficient of concordance, which is a non-parametric test, was used to determine the degree of agreement or disagreement of target group responses concerning the factors that influence the BPM practice in Nigeria. SPSS v. 23 was used to run the test; the obtained result showed high significance (Table 7). Hence, the study concluded that, there was a statistically significant degree of agreement between different groups of respondents.

Tab. 5. Kruskal-Wallis test for building production information, production management documents and project management techniques/tools

Variables	Mean	Respondents groups	Mean rank	Chi-square	DF	Asymp. Sig
Factors for Building Production Information						
Architectural drawing	3.80	Clients Consultants Contractors	44.80 41.85 45.07	0.314	2	0.855
Structural drawing	3.71	Clients Consultants Contractors	45.50 39.87 46.08	1.138	2	0.566
Mechanical drawing	3.22	Clients Consultants Contractors	45.52 43.80 43.20	0.130	2	0.937

Electrical drawing	3.32	Clients Consultants Contractors	47.48 40.11 44.68	1.169	2	0.558
Other special drawing	2.90	Clients Consultants Contractors	50.48 39.57 43.20	2.529	2	0.282
Specification document	3.59	Clients Consultants Contractors	47.52 37.81 46.32	2.534	2	0.282
Factors for Production Management Documents						
Construction programme document	3.57	Clients Consultants Contractors	42.46 42.80 45.84	0.378	2	0.828
Construction methodology document	3.16	Clients Consultants Contractors	39.61 46.06 45.23	1.043	2	0.594
Project health and safety plan document	2.84	Clients Consultants Contractors	47.85 43.28 42.18	0.810	2	0.667
Project quality management plan document	2.90	Clients Consultants Contractors	44.61 49.98 39.26	3.028	2	0.220
Early warning system chart document	2.21	Clients Consultants Contractors	35.63 51.59 43.66	5.381	2	0.059
Information requirement schedule document	2.21	Clients Consultants Contractors	35.67 51.78 43.50	5.673	2	0.059
Factors for Project Management Techniques/Tools						
Project in controlled environments (PRINCE/ PRINCE2)	1.40	Clients Consultants Contractors	39.41 48.81 49.51	4.254	2	0.119
In-house project management methods	2.41	Clients Consultants Contractors	36.85 42.54 49.51	3.986	2	0.136
Cost-benefit analysis (CBA)	2.11	Clients Consultants Contractors	38.57 47.33 44.95	1.737	2	0.420
Decision analysis (DA)	2.24	Clients Consultants Contractors	30.48 42.19 53.73	13.342	2	0.001
Buildability and maintainability analysis	2.55	Clients Consultants Contractors	34.48 43.50 50.28	5.951	2	0.051
In-house decision-making techniques	2.72	Clients Consultants Contractors	35.63 43.48 49.58	4.692	2	0.096
Programme evaluation & review technique	2.82	Clients Consultants Contractors	37.28 39.52 51.45	6.226	2	0.044
Project sensitivity analysis	2.68	Clients Consultants Contractors	38.85 40.91 49.46	3.330	2	0.189
Graphical evaluation & review technique	2.52	Clients Consultants Contractors	42.24 42.26 46.36	0.612	2	0.736
Line of balance	2.54	Clients Consultants Contractors	46.85 40.81 44.55	0.793	2	0.673

Critical path method (CPM)	2.85	Clients Consultants Contractors	50.41 41.65 41.73	2.174	2	0.337
Work breakdown structure (WBS)	3.01	Clients Consultants Contractors	49.20 35.20 47.19	5.173	2	0.075
Life-cycle cost analysis (LCCA)	2.79	Clients Consultants Contractors	48.50 37.70 45.80	2.768	2	0.251
Probability analysis (PA)	2.56	Clients Consultants Contractors	48.98 40.09 43.76	1.650	2	0.438
In-house risk assessment tools	2.60	Clients Consultants Contractors	43.96 46.39 42.28	0.445	2	0.800
Gantt bar chart	2.20	Clients Consultants Contractors	47.46 38.78 45.66	1.898	2	0.387

DF = degrees of freedom, ASYMP. SIG = significance level

Tab. 6. Kruskal-Wallis test for critical success factors

Critical success factors	Mean	Respondents groups	Mean rank	Chi-square	DF	Asymp. Sig
Time Factors						
Adequate experience of project participants	3.86	Clients Consultants Contractors	48.11 35.93 47.34	4.451	2	0.108
Effective site management and supervision	4.02	Clients Consultants Contractors	46.67 36.61 47.73	3.842	2	0.146
Realistic obligation/clear objectiveS	3.69	Clients Consultants Contractors	51.30 34.48 46.41	6.709	2	0.035
Adequacy of communication and coordination among parties	4.06	Clients Consultants Contractors	49.96 40.93 42.54	3.196	2	0.202
Rapid decision making	3.91	Clients Consultants Contractors	59.80 30.11 44.31	5.123	2	0.077
Cost Factors						
Frequent progress meetings	3.67	Clients Consultants Contractors	49.65 45.37 39.49	2.688	2	0.261
Availability of resources	3.94	Clients Consultants Contractors	47.02 37.80 46.65	2.612	2	0.271
Adequacy of raw materials and equipment	4.02	Clients Consultants Contractors	47.17 36.50 47.50	3.880	2	0.144
Eliminating waste	3.97	Clients Consultants Contractors	50.30 35.59 46.22	5.559	2	0.062
Effective contract administration and management	3.76	Clients Consultants Contractors	55.17 32.63 45.35	11.470	2	0.003
Quality Factors						
Effective quality assurance system in an organisation	3.84	Clients Consultants Contractors	56.83 35.76 42.04	9.920	2	0.007

Effective monitoring and feedback by project participants	3.82	Clients Consultants Contractors	45.63 35.04 49.53	5.984	2	0.050
Availability of a competent team	3.99	Clients Consultants Contractors	47.78 35.11 48.14	5.668	2	0.059
Quality of equipment and raw materials	3.91	Clients Consultants Contractors	47.35 41.98 43.39	0.698	2	0.705
Effective corporation among project parties	3.78	Clients Consultants Contractors	48.09 35.41 47.73	5.133	2	0.077
Health and Safety Factors						
Implementation of the safety management system	3.60	Clients Consultants Contractors	49.80 37.78 44.93	3.167	2	0.205
Provision and delivery of appropriate safety training	3.54	Clients Consultants Contractors	48.63 35.65 47.22	4.864	2	0.088
Adequate number of site safety representatives	3.38	Clients Consultants Contractors	51.13 41.76 41.20	2.702	2	0.259
Involvement in the safety awareness of project participants	3.46	Clients Consultants Contractors	56.96 33.69 43.47	11.739	2	0.003
Conducting regular safety meeting or toolbox talks on site	3.44	Clients Consultants Contractors	47.24 35.83 47.95	4.462	2	0.107
Environment Factors						
Regular maintenance of equipment for the project	3.84	Clients Consultants Contractors	50.48 37.26 44.89	3.953	2	0.139
Sufficient provision of environmental management training	3.45	Clients Consultants Contractors	55.61 36.87 41.99	8.115	2	0.017
The use of up-to-date technology	3.63	Clients Consultants Contractors	59.20 37.15 39.55	12.658	2	0.002
Use of environmentally friendly equipment	3.76	Clients Consultants Contractors	49.30 30.59 50.49	12.193	2	0.002
Proper environmental site planning	3.75	Clients Consultants Contractors	50.85 41.28 41.73	2.610	2	0.271
Productivity Factors						
Availability of skilled workers	3.94	Clients Consultants Contractors	56.04 41.06 38.66	8.806	2	0.012
Clear and timely inspection	4.07	Clients Consultants Contractors	52.15 41.70 40.61	4.161	2	0.125
Effective change order management	3.79	Clients Consultants Contractors	52.35 36.44 44.32	5.859	2	0.053
The efficiency of tools and equipment	3.94	Clients Consultants Contractors	45.87 32.09 51.53	10.439	2	0.053
Availability of financial motivation system	3.80	Clients Consultants Contractors	46.26 37.41 47.41	3.077	2	0.215

Risk Management Factors						
Effective control of third-party delays	3.62	Clients Consultants Contractors	51.48 32.00 48.11	10.083	2	0.006
Absence of defective materials	3.79	Clients Consultants Contractors	51.02 31.11 49.04	11.170	2	0.004
Availability of funds as planned throughout the project duration	3.95	Clients Consultants Contractors	52.59 30.33 48.64	13.070	2	0.001
Implementation of an effective site safety management programme	3.86	Clients Consultants Contractors	45.52 37.37 47.89	3.184	2	0.204
Adequacy of risk management techniques	3.60	Clients Consultants Contractors	45.07 40.93 45.58	0.664	2	0.718
Human Resource Factors						
Availability of skilled personnel	3.90	Clients Consultants Contractors	43.67 42.57 45.24	0.203	2	0.904
Adequacy of skill training and development for all employees	3.71	Clients Consultants Contractors	53.20 39.15 41.82	4.785	2	0.091
Effective monitoring and feedback	3.84	Clients Consultants Contractors	48.33 37.28 46.22	3.323	2	0.190
Spirit of cooperation among project team members	3.75	Clients Consultants Contractors	42.63 39.02 48.49	2.518	2	0.284
Availability of internal promotion	3.69	Clients Consultants Contractors	54.76 38.52 41.31	6.458	2	0.040
Client Satisfaction Factors						
The durability of the completed work	4.10	Clients Consultants Contractors	47.96 33.37 49.30	8.037	2	0.018
Aesthetic of the completed work	4.13	Clients Consultants Contractors	46.17 35.37 48.95	5.416	2	0.067
Timeliness of service	4.00	Clients Consultants Contractors	41.50 35.30 51.91	8.122	2	0.017
Efficient functionality of product/service	3.91	Clients Consultants Contractors	52.61 34.37 45.68	7.451	2	0.024
The professionalism of project team services	4.10	Clients Consultants Contractors	52.89 34.11 45.69	8.113	2	0.017

DF = degrees of freedom, ASYMP. SIG = significance level

Tab. 7. Test statistics for Kendall's coefficient of concordance

Number (N)	87
Kendall's (W^a)	0.277
Chi-Square	1733.397
Degrees of Freedom (DF)	72
Significance Level (Asymp. Sig.)	0.000

4. Discussion of the results

Ineffective building production management (BPM) is one of the causes of poor project performance. In Nigeria, the BPM practice and its effect on project performance still face disagreement/misunderstanding. The current study uses Nigeria as a representative case to provide some in-depth insights into the BPM practice used by construction stakeholders. The study identified several items that were very important for the BPM practice to be effective and grouped them into three categories, namely, building production information, building production management documents and project management techniques/tools. The study found that "architectural drawings" and "structural drawings" were most important pieces of building production information while "the construction programme document" and "the construction methodology document" were the most important building production management documents. Also, in terms of project management techniques/tools, "the work breakdown structure (WBS)" and "the critical path method (CPM)" were found to be the most important.

In the study, architectural and structural drawings were identified as the top two pieces of production information from among the six named, and possibly these drawings are required by a construction contractor before anything else. An architectural drawing is important as it shows client demands for a construction project. In the same vein, a structural drawing is considered important for the stability of the building project. Building production management documents are documents used in construction planning and site production management. This study found that the construction programme document and the construction methodology document were the most important for a construction project. The studies by Okoye and Ngwu (2015) found a low level of awareness and extremely low use of documents, such as the project health and safety plan, construction programme and project quality management plan. Put together, the importance of these documents for building production management is yet to be recognised. The reason behind the failure to use the documents could stem from negligence or the lack of effective control and regulation in the building system of Nigeria. In addition, the study participants considered the work breakdown structure (WBS) and the critical path method (CPM) as the most important project management techniques/tools. This situation could be the result of their simplicity and user-friendly nature or limited knowledge of the project management techniques/tools. The findings are consistent with those reported by the earlier studies. For example, Haron et al. (2017) found that CPM, CBA, and the Gantt bar chart were the most widely applied project management tools and techniques in the construction sector. Ugwu and Attah (2016) also found that the critical path method (CPM) was the most important project management technique that influenced the management of construction projects.

The effective use of building production information, production management documents and project management techniques/tools in the construction industry would provide stakeholders with headway to attaining project goals. The study into the use of drawings, construction documents, management techniques and tools that are widely applied in the industry, will help contractors and other stakeholders to create strategies for the built environment aimed at the efficient and effective application of the BPM practice. When these drawings, construction documents and management techniques are properly implemented, the BPM practice certainly results in adequate benefits at every part of project execution.

Furthermore, among the nine groups of critical success factors, the study identified the top nine, which have the most influence on project success, including "adequacy of communication and coordination among parties (the time factor)", "adequacy of raw materials and equipment (the cost factor)", "availability of competent team (the quality factor)", "implementation of a safety management system (the health and safety factor)", "regular maintenance of equipment for the project (the environment factor)", "clear and timely inspection (the productivity factor)", "availability of funds as planned throughout the project duration (the risk management factor)", "availability of skilled personnel (the human resource factor)", and "aesthetic of the completed work (the client satisfaction factor)". The findings are consistent with results reported in earlier research. For instance, studies by Homthong and Moungnoi (2016) revealed the most critical factors that determine project success, including the competence of project participants, the durability of completed work, the relationship between project participants, the positive attitude of employees, an effective quality assurance system in an organisation, the quality of works to match standards, the interrelation between an employee and a supervisor, competent supervisors and regular maintenance of project equipment. Haron et al. (2017) identified top five critical factors that influence the project success, including the competency of the project team, customer satisfaction, realistic cost and time estimation, effective planning and controlling, and financial attributes. The idea behind critical success factors rests on the identification of aspects that can lead to project success. The characteristics of the construction industry could be the underlying reason for the observed consistency.

The findings of this study provide insight into the BPM practice and factors influencing project success in the construction sector. As the study particularly focused on a developing country like Nigeria, its findings may not be generalisable, therefore must be applied with caution.

Conclusion

The study highlighted factors that influence the BPM practice in Nigeria construction industry, such as architectural drawings, the construction programme document, the work breakdown structure, the adequacy of communication and coordination between parties, the adequacy of raw materials and equipment, the availability of a competent team, the implementation of a safety management system, regular maintenance of project equipment, a clear and timely inspection, the availability of funds as planned throughout the project duration, the availability of skilled personnel, and aesthetics of the completed work. Based on the research findings, the building production information is considered of moderate importance in the management of building projects in Nigeria. The result of the analysis revealed that architectural drawings, structural drawings and the specification document were important factors relative to building production information. For the category of production management documents, two factors were moderately important, namely, the construction programme document and the construction methodology document, while others were slightly important. Project management techniques/tools are essential in construction management. The findings from the data analysis showed that the work breakdown structure was moderately important, and the remaining 15 factors that were relative to project management techniques/tools were either slightly or least important. This is as a result of the lack of adequate knowledge of these management techniques/tools, which is not helpful for building construction management. The concept of project performance criteria presents a meaningful way to identify factors that can lead to project success. The analysis revealed that for project success, adequacy of communication and coordination among parties is especially important in terms of time factors, adequacy of raw materials and equipment – cost factors; clear and timely inspection – productivity factors; and durability and aesthetics of the completed work as well as the timeliness of service and professionalism of the project team – client satisfaction factors.

The study recommends for the government of Nigeria to enact and enforce the law on the practice and implementation of BPM by qualified professionals only. This act will fish-out quacks in the building in would prevent unqualified individuals from accessing the building industry, which should reduce or even completely eliminate cases of building failures. All the building production information, including the production management documents, should be made compulsory by the government for the execution of every building project in Nigeria and such documents should be signed and stamped by relevant stakeholders. Proper monitoring and controlling of execution of building projects on site by relevant agencies should be effective and efficient so as to ensure good practice in the system. In addition, academia should contribute to adequate training and retraining on project management techniques/tools for project managers and encourage their use in the implementation of BPM.

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Methodology for bottleneck identification in a production system when implementing TOC

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ABSTRACT
For TOC (Theory of Constraints) implementation in a production system, the determination of the system's bottleneck is a crucial step. Effective bottleneck identification allows setting priorities for the improvement of a production system. The article deals with a significant problem for the manufacturing industry related to the location of a bottleneck. The article aims for a detailed analysis of methods for bottleneck identification based on a comprehensive literature review and the design of a generalised methodology for bottleneck identification in the production system. The article uses two research methods, first, the combination of a narrative and scoping literature review, and second, the logical design. Several methods for bottleneck identification are reviewed and compared, finding some being similar, and others giving new insights into the evaluated production system. A methodology for bottleneck identification is proposed. It contains several detailed methods arranged in coherent steps, which are suggested to be followed when aiming for the recognition of a production system's bottleneck. The proposed methodology is expected to be helpful in the practical TOC implementation. The presented methodology for the identification of bottlenecks in a production system is a practical tool for managers and experts dealing with TOC. However, it is still a conceptual proposal that needs to be tested empirically. The proposed methodology for bottleneck identification is an original concept based on the current literature output. It contributes to the production management theory as a practical managerial tool.

KEY WORDS
Theory of Constraints, TOC, production improvement, bottleneck identification, constraints

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Introduction

A determined primary objective is a prerequisite for the proper operation of a business. It is often believed that the mission of a business is to manufacture and sell products, enter new markets, and use the latest technologies. However, those are nothing but means to influence the ability of a business to succeed in achieving its real objective: making money. A business must take the required steps to reach its objective as efficiently as possible and eliminate unproductive activities. To achieve this aim, the throughput must be improved by changing factors which constrain the

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production system. A critical step is to identify and focus on the constraints, the improvement of which would better the entire production system.

The traditional approach to management claims that constraints of a system should be reduced or even eliminated (Skołud, 2006; Skołud, 2009). Proper management of constraints requires appropriate methods and tools (Łopatowska, 2008). One of them is the Theory of Constraints (TOC).The Theory of Constraints was formulated by the Israeli physicist Eliyahu M. Goldratt. According to TOC, one cause may lead to many harmful consequences. A cause is identified as a constraint of a system that requires attention (Trojanowska & Koliński, 2015). The underlying assumption of TOC is that the capacity of the entire production system of a business depends on the capacity of the constraint. The Theory of Constraints focuses on the identification of constraints in production systems and their proper management to achieve the maximum throughput (Łopatowska, 2017).

A constraint is the most important element in the TOC method. It determines the capacity of the production system and limits its success. There are three types of constraints. The first type is the resources. A manufacturing company has a greater capacity than it thinks. An excess of production capacity is characterised by a surplus of stock of finished products and work in progress. Constraints related to resources may be present within a business, e. g., bottlenecks of the production system, that is production capacity limited by an insufficient number of employees or work time of a machine, or outside of the business, e. g., an inappropriate marketing strategy or changing demand. Another type of constraints is materials. This constraint is rather infrequent. An example is a problem with suppliers of universally available materials. The last type of constraints is related to the policy of a business. This includes all measures, principles, factors, and paradigms that define the ways used to manage the business and that influence the development of its policy. They are the cheapest and most frequent subject to remedy. An example of such a constraint is minimum employment, which does not always bring advantageous results (Woeppel, 2009; Koliński & Tomkowiak, 2010).

The identification of a constraint is the basis for improvement of a production system. The presence of constraints, that is, factors that limit the ability of a business to increase its profits leads to the use of tools that enable the improvement of business efficiency. "Five Focusing Steps" is a systematic constraint management method and a continuous improvement process suggested by Goldratt, which is based on five stages: the identification of a constraint, the exploitation of the constraint, subordination, the increase of the throughput of the constraint and the return to the first step. The objective of this method is to transform the weakest links of a production system into efficient and effective resources (Ikeziri et al., 2018). A procedure conforming to the five stages is shown in Fig. 1.

The recognition of constraints in a production system is of key importance. Therefore, the first step is to determine the exact location and to indicate the resource that limits the capacity of the production system to the greatest extent. To find a problem, it is necessary to identify its root cause. According to TOC, improvement of other elements of the system does not affect the efficiency of the entire system (Lisiecka, 2013).

The next step is the maximum exploitation of the constraint. This consists of the elimination of all things that result in a time deficit in a resource that constrains

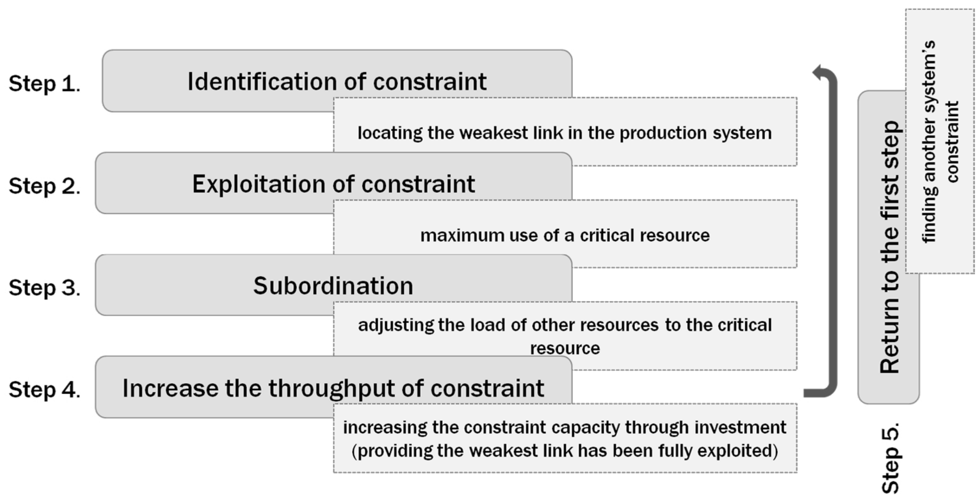

Fig. 1. Five Steps Cycle

the production system. Actions must be taken to ensure the continuous operation of the constraint to improve the efficiency of the system without incurring any additional expenses.

The third step is the subordination to the decision made in Step 2. This consists of the adaptation of the work pace of other resources to the work pace of the resource that constitutes a constraint. The remaining resources should not produce more than the constraint is capable of processing, and whatever is supplied must match the needs of the constraint (Wrodarczyk, 2013).

The fourth step is to improve the efficiency of the constraint. This stage makes it possible to improve the functioning of the constraining factor by way of possible investments. However, before this step is taken, the weakest link must be fully exploited. It must be remembered that the elimination of a constraint in one place leads to the occurrence of other constraints. It is important to constantly improve the production process by searching for and overcoming constraints (Li et al., 2010).

The research of manufacturing constraints and their appropriate identification is the key to improving production capacity and stability. Constantly developing companies that seek for continuous improvement have a stronger competitive edge in the market. The literature does not offer comprehensive and practical solutions and guidance supporting constraint identification in companies. The knowledge of the bottleneck allows increasing the throughput by streamlining a single process. The study by Urban (2019) showed that the bottleneck in the production system was not obvious and required to analyse the system as a whole. As methods used by the author showed various bottlenecks, this step in constraint management requires further research and practical guidance. Clear guidance is needed on how to identify a bottleneck.

The article aims for a detailed analysis of methods for bottleneck identification based on a comprehensive literature review and the design of a generalised methodology for bottleneck identification in a production system. The proposed concept of bottleneck identification aims to meet managerial needs for clear guidance regarding the practical recognition of a bottleneck location in a manufacturing system.

The study has the following structure. The first chapter presents the results of the comprehensive literature review concerning methods of bottleneck identification. Several methods for bottleneck identification are reviewed and compared. The next chapter describes the research methodology. In the third chapter, the authors of the article present their methodology for bottleneck identification in a production system, which can be helpful for production managers and experts implementing TOC. The final part analyses results and conclusions. A number of solutions and guidelines for applying the developed methodology in practice are proposed.

1. Literature review

The identification of a bottleneck is the first and most important step towards the improvement of a business production capacity. It is the key stage of the continuous improvement process. It is also the first step in constraint management according to the Theory of Constraints. The literature on this topic identifies many methods for the identification of bottlenecks in a production system. Table 1 shows a summary of bottleneck identification methods.

The Process Time method focuses on the measurement of the material flow time in processes. This approach indicates the maximum efficiency of a process in the tested conditions (Roser et al., 2014).

The Average Active Period and Active Period methods focus on the time when a machine is active continuously. The activity of a machine is defined as the time of operation of a machine, waiting for another machine, repair, or tool replacement. The aforementioned methods identify bottlenecks as processes with the longest average active time or temporary bottlenecks as processes with the longest instantaneous active periods. These methods use extensive process data (Roser et al., 2002).

The Longest Waiting Time method focuses on measuring the utilisation of machines in the production process. The machine which is utilised to the greatest extent is considered to be the bottleneck. In this method, accurate results require longer observations and measurements. This method is limited to stationary production processes (Law & Kelton, 2000).

Another recommended method is the Longest Queue method which analyses the length of a queue or the waiting time of machines in a production process. A machine with the longest queue or the longest waiting time is considered to be the bottleneck. This method is able to detect instantaneous bottlenecks (Betterton, 2012).

The Inactive Period method is an approach that determines a bottleneck in a place where the shortest time is spent in the inactive status.

The Utilisation method is also known as an effective process time method. It is used in mass production where the number of parts is the same at each station. A bottleneck is detected by calculating the utilisation

Tab. 1. Bottleneck identification methods

Name	Approach	Reference
Longest Queue	length of a queue analysis or a measurement of the waiting time of machines	Lawrence and Buss (1994)
Longest Waiting Time	rate of utilisation of machines measurement	Law and Kelton (2000)
Utilisation	rate of utilisation of machines measurement	Hopp and Spearman (2000)
Average Active Period/ Active Period	measurement of the machine activity continuously	Roser et al. (2001/2002)
Process Time	material flow time in process measurement	Delpf et al. (2003)
Queue Time/ Average Waiting Time	the waiting time before the process measurement	Faget et al. (2005)
Inactive Period	inactive time of machine measurement	Sengupta et al. (2008)
Turning Point	observation of blocking and waiting of processes	Li et al. (2009)
Bottleneck Walk	observation of processes and the level of inter-process resources	Roser et al. (2014)
Flow Constraint Analysis	takt time and the resource cycle time comparison	Sims and Wan (2017)
C/T Corrected	cycle time and the degree of utilisation of each process measurement	Urban (2019)

of each resource. A station with the highest degree of utilisation is considered to be the bottleneck of the production system (Dongping et al., 2014).

The Bottleneck Walk method consists of the observation of processes and of the level of inter-process resources. This method does not require measurements, calculations, or statistics. According to this method, if a process waits for parts, then the bottleneck is somewhere upstream of that process. On the other hand, if a process is blocked because it cannot hand over parts to another process, then the bottleneck is located downstream of the blocked process. Another source of information is inter-process buffers. If a buffer between processes is full, then the bottleneck is located further in the production processes; if a buffer is empty, the bottleneck is located upstream of the buffer. If a buffer is half full, the bottleneck can be on either side. These assumptions indicate the direction where the bottleneck can be found. During observation of the production process, the direction of the bottleneck must be noted. A bottleneck is located between arrows that face each other (Roser et al., 2014).

The Turning Point method consists of the observation of mutual blocking and waiting of processes. The turning point is a process whose share of the work time is the largest of all the neighbouring processes. A turning point is not present when the process waiting time is longer than the blocking time. If the waiting time of each process is longer than the blocking time, the bottleneck is considered to be the first process. Otherwise, the bottleneck is the last process.

The Queue Time method, also referred to as the Average Waiting Time method, consists of measuring the waiting time before a process. A process upstream with the longest average waiting time is considered to be the bottleneck (Yua & Matta, 2016).

The Flow Constraint Analysis method is an approach that evaluates customer demand. A bottleneck of a production process is identified by comparing the takt time and the resource cycle time in a production system. If the cycle time of a machine is longer than the time required to perform an order, then this resource is the bottleneck of the production system. Another approach of this method is the indicator of the utilisation of the spare capacity of a machine. Spare capacity is the difference between the cycle time and the takt time. A bottleneck in a production system with different cycle times is identified by the highest utilisation of a resource (Sims & Wan, 2017).

The Corrected C/T method focuses on measuring the cycle time and the degree of utilisation of each process in the production stream. The product of C/T and the process utilisation indicator is the actual time needed to make a product. The calculation of the efficiency of processes by the corrected C/T indicates the process that constitutes a bottleneck (Urban, 2019).

Other methods of bottleneck identification can be considered as some of the various mathematical approaches. Dongping et al. (2014) suggested an algorithm for the detection of bottlenecks in complex assembly lines. Chiang et al. (2002) analysed the impact of machines on bottlenecks.

In conclusion, different bottleneck identification methods are available in the literature. Some of them are remarkably similar, e. g., the Longest Waiting Time and Utilisation, and some are different, e. g., Process Time and Bottleneck Walk. Some methods provide a fresh look at the production system being evaluated, e. g., C/T Corrected. Most of the available methods can be considered having at least one or more disadvantages, e. g., in terms of their use in different production systems. Some methods require extensive process data that are not always available; long term data collection; detect temporary bottlenecks, or are only applicable to selected types of production systems. Many available methods use machine data. In this case, the accuracy of the bottleneck finding may be related to data variability. This variability can be caused by unplanned machine downtime, setting machine parameters, repairing or changing process times. Therefore, bottleneck identification based only on data can be incorrect and unreliable.

The literature provides bottleneck identification methods that are separate, single methods. The production manager can choose an appropriate method and apply it. However, the chosen bottleneck identification method does not guarantee the real result of the bottleneck in the process. It is, therefore, considered that the problem should be approached comprehensively. Therefore, the authors attempted to develop a bottleneck identification methodology, which would facilitate the search for the bottleneck and could be used in practice. The proposed methodology is expected to be a practical tool for TOC implementation.

2. Research methods

Aiming at a detailed analysis of methods for bottleneck identification, the systematic literature review methodology was employed. The review of the publication was based on the EBSCOhost database. The selection of the database was based on the availability of full-text content and size database. Publications were collected based on the wording "bottleneck identification in production". The selected phrases were searched in titles, abstracts and keywords of publications. The time frame of the analysed period covered ten years, from 2009 to 2019. Additional conditions limiting the search were full version text and published in scientific journals. The obtained set of publications was subjected to content analysis. The largest number of publications directly related to the production system were obtained in the following journals:

- International Journal of Production Research,
- Mathematical Problems in Engineering,
- Robotics and Computer-Integrated Manufacturing,
- Logistics Research,
- Production and Manufacturing Research.

The substantial part of the literature review is presented above; however, it also contributes noticeably to the conceptual design referred to in the following parts. The second research work stream is on the design of the methodology for the bottleneck identification in a manufacturing system. In this task, the conceptual design approach was employed. The conceptual design method is widely practised in many fields of problem-solving, such as engineering, product development and manufacturing systems (Christophe et al., 2014; Thompson, 1999; French, 1999). The literature mentions the conceptual design as modelling by using precise and neutral concepts coming from needs or ideas (Christophe et al., 2014). According to Thompson (1999), a design concept defines and describes the principles and features of a system. In this particular task, the conceptual design is about the elaboration of the way of proceeding when determining the system bottleneck according to TOC. This design of a procedure applicable to any manufacturing system is based on already known methods and techniques, which were presented in the literature.

3. Bottleneck identification methodology

Bottleneck identification is a key element in the examination of production systems, which has the greatest impact on the efficiency of the entire system. Fig. 2 shows the proposed bottleneck identification methodology. The methodology is a collection of bottleneck identification methods. Some of those methods are available in various publications on this topic.

The first step to be made in the detection of a bottleneck in a production system is an analysis of the production flow and division into processes (#1). Direct observation of a process must be conducted. When determining the processes performed in a business unit, one must focus not only on production processes. A bottleneck can be found in logistics operations, warehousing operations, and even the information flow. Therefore, it is important to perform an accurate and detailed analysis of the production flow and the mutual relationships between the processes.

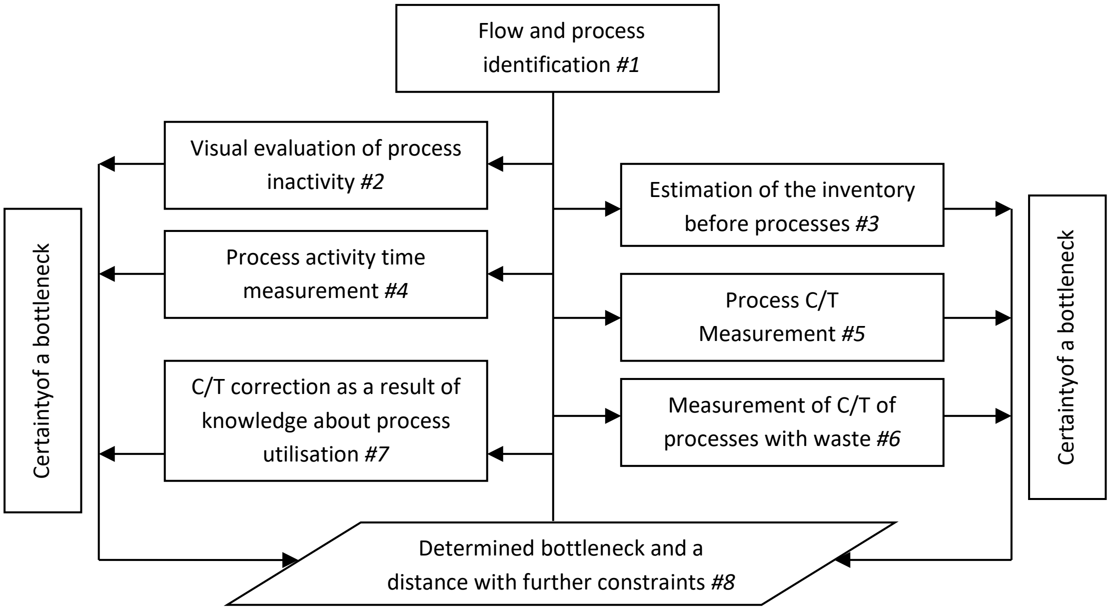

Fig. 2. Bottleneck identification methodology in the production system

The next suggested step is a visual evaluation of process inactivity (#2) based on observation. This enables the identification of processes that are inactive. Process inactivity can preliminarily exclude processes that are not the bottlenecks in the production system. It is important to think during observation why a specific process is inactive. If the operator is absent from a workstation, the possibility must not be excluded that the relevant process is not a bottleneck. Based on one observation, it is impossible to identify processes that are not bottlenecks.

The next suggestion is to estimate the inventory before processes (#3), in other words, stocks. This technique corresponds to the recommendation made by Roser et al. for the Bottleneck Walk method (Roser et al., 2014) and is very similar to the Longest Queue method mentioned by Lawrence and Buss (1994). It requires observation of the stock created between processes and their optimum level. If necessary, the stock size needs to be counted systematically and/or taken from the IT system. The issue is not the largest stock in numbers but the "longest" stock that is measured by the process occupation. A large quantity of stocks indicates that the bottleneck of the production process is located downstream of the stock. To confirm the presence of a bottleneck using inter-process stocks, it is recommended to conduct at least two observations with some time between them. The observations must be conducted in two directions: down and up the process line.

To identify a bottleneck, the process activity time (#4) can be measured. Publications on this topic describe multiple methods that utilise this indicator. These are the Average Active Period, Active Period (Roser et al., 2002), and Inactive Period (Dongping et al., 2014). The process activity time can be measured depending on the available data. The first approach consists of data-taking from the machine monitoring system. Another approach consists of the observation and measurement of the process work time for a period that ensures acceptable credibility. The process that has the longest active time is the bottleneck.

The next suggested step is the measurement of the cycle time of each process (#5). This indicator makes it possible to determine the real-time between the production of successive products in the process. Depending on the division of the flow into processes, this can also be, e. g., the loading time or the transport time. The process with the longest cycle time is considered to be the bottleneck.

The next method is the measurement of the cycle time of the process considering the waste (#6) occurring in the process. The consideration of all waste present in a process indicates the real availability of a process. Waste present in a process includes conversions, repairs, and setting of machines, non-productive time, and products that do not meet applicable quality standards. Like in the previous method, the process with the longest cycle time is considered to be a bottleneck.

The next suggested step that enables the detection of a bottleneck is the use of the corrected C/T (#7) method recommended by Urban (2019). This method requires to know the production structure and measure the process cycle times and the individual utilisation of a process in the manufacture of a product. The product of cycle time and the process utilisation indicator constitute the actual time needed to make a product. A process with the lowest efficiency (highest process cycle time) is the bottleneck of a production system.

The recommended methods provide tips regarding methods for the detection of a bottleneck in a production system. The identification of flows and processes is the key stage in the identification of bottlenecks. In the case of other elements, the use of all methods is not necessary. If only several methods have enabled the identification of a bottleneck and the calculation of the distance to the next constraint, it is not necessary to perform the remaining steps. According to Urban (2019), the detection of a bottleneck and the implementation of improvement actions result in the improvement of the efficiency of a production system. However, the calculation of the distance to the next constraint is an important element. The distance to the next constraint is the scale of the lacking efficiency compared to the next process. It is required to know the scale of the necessary actions to exploit the bottleneck.

4. Discussion of the results

Goldratt claims that each system has at least one bottleneck, which effectively constrains the full exploitation of the company's production potential. Therefore, their identification becomes crucial because only then will the system's throughput improve. The analysed literature shows that this step is not a simple and obvious task. The bottleneck identification methods proposed by other authors are stand-alone methods. However, the use of a single (often random) method will not provide a reliable answer as to the location of the actual bottleneck and the suitability of the method for this type of the production system. It is expected that the proposed methodology for the identification of a bottleneck in a production system will be a practical tool in the TOC implementation for managers and experts. The methodology provides several tips and possible steps that can be taken by production managers. These steps are not random but rather indicate a coherent approach to the production system. They allow assessing the system as a whole and getting to know in detail.

The observation of the flow and its division into processes are the key stages in the detection of bottlenecks in production systems. Once a bottleneck has been identified using the discussed methods, it is important to understand why a given process is a bottleneck. A recommended tool that can be used to find the cause of the problem is the 5-Why method. The identification of the cause of the problem makes it possible to implement effective corrective measures that will result in improved efficiency of the production system.

In step #6 (the measurement of the cycle time considering waste), a division of the waste can be used that is present in the OEE indicator. Waste is classified based on three parameters: availability, efficiency, and quality. When analysing waste in a process, particular attention must be paid to (1) events that cause production downtime, e. g., breakdowns, conversions, setting of machines, and production changes; (2) factors that cause the production process to be slower than the maximum efficiency of the process, e. g., start-up of machines; (3) events that cause loss of quality, e. g., the reduced efficiency of a machine during start-up.

In addition to the identification of a bottleneck, it is also important to calculate the distance from the identified bottleneck to the next constraint. The calculation of the distance to the next constraint requires to at least measure the process C/T (#5) or the process activity (#4). The detection of a bottleneck and its difference from other processes with regard to efficiency enables a company to take appropriate steps to increase the flow through the bottleneck.

An additional issue is the production system that uses the Lean Manufacturing approach, where the principle of the pull system (Womack & Jones, 1996) is toughly introduced into the manufacturing flow, where the material flow is controlled by Kan-Ban system (Puchkova et al., 2016) and where, e. g., a substantial part of the production flow is organised according to the One Piece Flow method (Eaidgah et al., 2016). The Kan-Ban system relies on pulling small production batches (containers of limited capacity). In such a system, the level of the stock between two cooperation workstations is determined by the number of Kan-Ban cards admitted to the system. If the number of cards determines the stock, the system bottleneck cannot be recognised by the level of waiting/queuing material. However, the bottleneck will be manifested by inactivity at work stations that are not bottlenecks, and the bottleneck will be fully loaded. So, the Process activity time measurement (#4) and the Process C/T measurement (#5) mentioned in Fig. 2 can be fully applicable in these cases. It must be underlined that one important purpose of Kan-Ban, like One Piece Flow, is to balance the manufacturing flow, which implies discovering bottlenecks in the manufacturing value stream and their resolution (Rother & Shook, 1999; Liker, 2004; Hino, 2006). It may be concluded that bottleneck identification is immanently tied to the Lean Manufacturing approach.

The literature also mentions the appearance of a shifting bottleneck (Thürera & Stevenson, 2018) in the manufacturing system. It means that a bottleneck changes its place in the manufacturing systems due to different circumstances. Is such a case, potentially each of the presented bottleneck identification methods can be used; however, production managers need to have convenient methods prepared to quickly find the answer to the question "Where is the current bottleneck?"

Conclusions

The identification of bottlenecks is important to every company. Bottlenecks have the greatest impact on efficiency because they dictate the pace of the entire production process. The article presented a detailed analysis of methods for the identification of bottlenecks in production systems based on a comprehensive review of publications on this topic. The methods can be divided into two groups. The first group of methods is based on at least one indicator related to the operation of machines or inter-process stocks. The second group of methods is mathematical algorithms.

A method for the detection of bottlenecks in a production system has been developed and constitutes a collection of the bottleneck identification methods that have been described in various publications on this topic. The key stage of this method is an in-depth analysis of the production flow and its division into processes. This makes it possible to understand and evaluate the current status of the system. The recommended method does not require the performance of all the suggested steps. A search for a bottleneck must continue until certainty is reached that a given process is a bottleneck in the system and until important parameters are calculated, based on which it is possible to determine the distance to the next constraint. The recommended method is a flexible tool that can be used for a broad range of production systems.

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Organisational competence vs transferability of knowledge in cluster organisations and technology parks

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ABSTRACT

The main paper aims to evaluate the impact of organisational competence on knowledge and information flows within cluster organisations and technology parks, with particular emphasis on innovative content knowledge. The paper addresses the research question: "What set of competencies of cooperating companies allows access to information and knowledge in cluster and parks structures?" The authors report their findings from a quantitative study carried out in four cluster organisations and three technology parks functioning in Poland. The research sample covered a total of 269 enterprises: 132 cluster members and 137 park tenants. The primary method of data collection was a survey questionnaire. Data analysis was conducted using the interdependence of variables, ANOVA, and logistic regression. The research showed that the surveyed enterprises from both analysed groups preferred cooperation with partners of a similar level of competence development and the same or complementary scope of competence. This set of competencies of cooperating organisations also guaranteed better access to information and knowledge resources, including confidential information and new knowledge. This study additionally indicated that the knowledge creation activities performed by the cooperating cluster organisations depended on the proximity of the competencies of organisations as well as on the nature of the information, disseminated within the cluster organisations. The theoretical contribution is related to the results obtained by analysing the phenomenon of information and knowledge dissemination in cluster and park structures, revealing the impact made by the competence proximity of cooperating organisations on the access to this such resources. Thus, the findings supplement the state-of-the-art knowledge of the concept of industrial clusters by presenting a broader view on cooperation developed in geographical proximity, based on a set of various partner competencies.

KEY WORDS

cluster, cluster organisation, technology park, industrial park, competences, proximity, cooperation

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Introduction

In the context of the knowledge economy, business strategists associate regional clusters of affiliated companies and other institutions with a sustainable competitive advantage. Scholars highlight the benefits of the process of corporate cooperation or integration, both for the clustering companies and for the economic growth of the region (Ostergaard & Park, 2015). In most studies, a core implication is that positive clustering effects result from knowledge or Marshallian externalities (Tallman et al., 2004; Ostergaard & Park, 2015; Ter Wal & Boschma, 2011). The literature

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explains the effect of knowledge exchange based on reference to extensive local networks, a common institutional environment, and the geographic proximity of firms. As firms are linked with the cluster network of knowledge exchange, clustering may impact the variety of knowledge resources and capabilities of an individual firm.

In addition to structural and geographical proximity factors, there are other preconditions for the dissemination of knowledge among companies in regional or technological clusters. Routines and processes of an organisation enable the transferability of information within cluster companies, their access to knowledge and the capacity to exploit it in the activities of new knowledge creation. Processes and routines of an organisation are the mechanism, by which the organisation responds to the external environment (information or knowledge). In a capability-based theoretical perspective, organisational competence is the resource that enables an organisation to function or respond to the signals of the environment (Nelson & Winter, 2000; Teece et al., 1997). The scientific literature has given less attention to the impact made by the competence of organisations forming a cluster on the involvement of these companies in the knowledge creation activities, implemented following the principles of cooperation. However, in the practice of regional clusters in terms of the access to knowledge, innovative knowledge creation processes, and the factors influencing them are particularly important.

The research aims to empirically evaluate the impact of organisational competence on knowledge and information flows within clusters, as well as to evaluate how the dissemination of information about the cluster partners and cluster environment influences the transfer of innovative content knowledge within studied entities. In the study, a knowledge-based approach was applied to examining access to information and knowledge for cluster companies that fall into different categories of competencies.

The authors report the findings from their quantitative study based on an analysis of four cluster organisations and three technology parks operating in Poland. The research goes beyond the state-of-the-art knowledge in relation to the concept of industrial clusters, by exposing a broader view on cooperation developed in geographical proximity, based on a set of various partner competencies, especially since the authors included two types of organisations with cluster attributes. The choice of a cluster and park structures for the study was affected by the similarities observed between them. Cluster organisations, also named cluster initiatives (Sölvell et al., 2003; Lindqvist et al., 2013; Štverková & Mynarzová, 2017; Lis, 2018, 2019), are understood as formally established organisations, functioning at a higher level of aggregation, composed of institutional members that consciously joined them (Lis, 2018). With regard to park structures, they are organisations that support the development of entities located in them, especially in the area of innovation and technology transfer. Both cluster organisations and technology parks are instruments of innovation policy to foster the growth of firms and regions via networking. Both concepts emphasise the significance of geographical proximity for the development of relationships and cooperation among entrepreneurs, who undertake their operations under conditions characteristic not only to a particular locality but also a particular industry. Geographical proximity is also considered a source of a privileged position taken by enterprises in their access to knowledge, its generation and distribution. Therefore, technology parks can be treated as a special kind of cluster structure, with great geographical proximity. However, despite the similarities between cluster and park structures, the additional cognitive value comes from the possibility of comparing both groups of entities. Cluster organisations and technology parks differ at the level of geographical proximity (in parks, this dimension of proximity is much more developed than in cluster organisations functioning under a greater location dispersion of their members), as well as competence proximity, both in the aspect of the scope of competences (technology parks, due to the greater sectoral range, characterised by a greater variety of competences of the cooperating partners) and at the level of competence development (in parks, due to the requirement of innovation, there are higher entry barriers than in cluster structures, which can result in a higher level of competence). A comparative study will help to identify the differences and similarities among cluster and park structures. Although the study was conducted in Poland, it offers findings that may be interesting for other states, especially for European countries, with a similar innovation policy (including cluster-based policy) to that of Poland.

The paper is organised as follows. The first section contains a literature review on the issues of transferability of information and knowledge and organisational competence in clusters. Based on the literature review, three propositions were formulated and then tested in the empirical part. The second section provides a methodology description, while the third reports the empirical results. Finally, discussion and conclusions are provided in the final sections.

1. Literature review

1.1. Organisational competence and cluster competence

Based on the analysis of organizational competence from the theoretical perspective of knowledge management, authors acknowledge different levels of competence depending on the scale of performance and outcomes. Individual competence is relevant to individual performance and tasks within an organisation, and the competence of the group or organisation is relevant to the achievement of operational tasks important to the whole organisation.

The ontological perspective of the concept of competence clearly links two elements — ability (to do work, to act, to accomplish something) and expression (competence manifests itself through performance as a direct perception or measurement of the competence is impossible) (Miranda et al., 2017). As Danneels (2016) have noted, competence has material as well as cognitive components.

Obviously, competence as a complex of knowledge, skills experience, motives, and traits is a characteristic of individuals. Individual competencies are material and cognitive abilities of individuals that enable them to perform the job-producing results consistent in terms of functional requirements and in line with organisational environment restrictions (Boyatzis, 1982).

Organisational competence is not the sum of individual competencies, but rather a dynamic set of correlating and complementary competencies that function within organisational structures and enable organisation's sustainability and competitive advantage. Organisational performance in a defined environment to maximise the value generated by organisational resources is an expression of organisational competence that, albeit with different interpretations, is recognised in the evolutionary theory and strategic management literature (Table 1).

As some approximation, organisational competence is considered as an organisation's asset that is referred to as the mechanism that supports the organisation's response to signals of the environment (Nelson & Winter, 2000). In the capability-based theoretical perspective, the concept of competence is close to that of dynamic capabilities (Teece & Pisano, 1994; Teece et al., 1997). In the resource-based view, an organisation is characterised as a bundle of organisation-specific resources (Wernerfelt, 1995). Capabilities and compe-

Tab. 1. Theoretical perspective of organisational competence

Theoretical perspective	Competence content	Reference
Evolutionary economics (firm-level ontogenetic evolution)	The specific content of economic behaviour addresses the issue of basic behaviour continuity in terms of skills, routines, learning, cognition (elements associated with competence). Competence is built in evolution economics — organisations possess bounded rationality due to the lack of competence. Competence puzzle focuses on the role of learning and practice. Organisational routine is treated as an organisational analogue of individual skill. Routinised behaviour can be complex and effective	Nelson and Winter (2002)
Evolutionary economics (dynamic capabilities)	Dynamic capabilities as the source of competitive advantage. "Capabilities emphasise the key role of strategic management in appropriately adapting, integrating, and reconfiguring internal and external organisational skills, resources, and functional competences toward changing environment" (Teece and Pisano, 1994:1). Organisational competences are defined as distinctive routines or processes that are enabled by integrated clusters of firm-specific assets, individuals and groups (Teece et al., 1997:516). Firm's dynamic capabilities are determined by processes, positions and paths	Teece and Pisano (1994), Teece et al. (1997), Winter (2003), Eisenhardt and Martin (2000)
Strategic management theory (the core competence approach)	Define core competences as roots of competitiveness. Provide a competence-based organisation's concept. Identified methods for core-competence building	Prahalad and Hamel (1990)
Strategic management theory (resource-based view of the firm)	Propose an idea to look at a firm as a set of resources rather than products. Resources are defined as tangible and intangible assets, such as knowledge, routines (effective procedures) that are difficult to replicate. Capabilities and competences are identified as resources	Wernerfelt (1984), Wernerfelt (1995), Amit and Schoemaker (1993)

tencies are considered as resources that, under certain features of being valuable, rare, inimitable, non-substitutable, can be a source of competitive advantage for an organisation (Kogut & Kulatilaka, 2001; Santos & Eisenhardt, 2005). On the level of a firm, the competence theory recognises competence as the antecedent of an economic agent's ability to solve problems. Competence implications to inter-firm diversity assumption were stated in evolutionary-type research. In line with the arguments of the evolutionist theory concerning the factors and mode of decision-making behaviour, Dosi & Marengo stated, that "competences represent the problem-solving features of particular sets of organizational interactions, norms and explicit strategies" (Dosi & Marengo, 2000, p. 53). If decision-making episodes are considered to be a challenge for individuals, groups or organisations in terms of problem-solving ability, this definition of competence reveals that organisational forms (i.e., particular sets of organisational interactions, norms, strategies) have an influence on decision-making, and competence affects the behaviour of economic agents. Based on this theoretical perspective, economic agents use their competence to compete for best (i.e., optimal) decisions. Competence is defined as a specific asset of a firm that is supported by the use of organisational knowledge relevant to determine performance outcomes that maximise the opportunity value of the resources portfolio of the organisation. However, organisations perform as systems with interconnected actions of individual decision-makers, and this raises some problems of causal ambiguity about the courses of organisational outcomes and inefficiency in terms of possibility to find some optimal solution (Cohen, 1987). Dosi and Marengo considered cognitive and political arguments regarding the basis of an organisation's common knowledge and hierarchical relations inside the organisation that relate diversity of preferences of individual decision-makers with the possibility to enhance various organisational knowledge and its adaptability (Dosi & Marengo, 2000, p. 59). Organisational architecture and routines of a performance organisation enable the firm to generate an efficient outcome in the use of endowments. The perspective of knowledge-based organisational competence primarily focused on a few epistemological assumptions. First, competence is represented by the decision-making power of members in the organisation, which depends on the information processing capabilities and learning; second, in theory, the aim of problem-solving entails the optimum action response of the organisation to environmental signals. The decision-making context involves the relationship between an organisation and the environment, in which it operates, and also internal rules that govern the behaviour of the organisation. Third, as a decision agent do not possess perfect decision procedures appropriate for a rational solution, and perfect information is not available, problem-solving solutions are the outcomes of emergent computation and interpretation. The problem-solving knowledge or competence in empirical grounds is related to the procedures or routines that are learned via experience and adaptation gained during actual problem-solving activity.

Some authors attribute the competence consideration to the meso-level unit of analysis — the regional competence (Niosi & Bas, 2005, p. 32). Industrial regions, as well as organisations, exploit endowments and possess some core competences that create a competitive advantage for regions. Regional competences comprise competences of individual organisations located in the regional proximity. As far as a regional competence is based on common knowledge that allows different organisations to coevolve, one particular competence — the capacity to cooperate — is considered the contingent upon the interaction within the multiagent setting. Different firms participating in the regional cluster have different aims and divergent systems of preferences; however, the cooperation is available on the basis of some harmonised aims (Lis, 2018, 2019). Problem solving actions within a group of interrelated organisations is based on the set of competences available to individual firms. Action modelling within a group of interrelated economic agents requires even more coordination and communication efforts as compared to the multiagent setting of an individual organisation. Regional competence as the knowledge gained from experience and learning includes not only knowledge shared by companies participating in regional cooperation but also inter-organisational communication structures that allow forming and disseminating common rules and routines. The development of common rules support relationships built inside the group of organisations and knowledge spillovers. As Heraud (1997) suggested, the interaction between companies located in regional proximity influences knowledge-creation and performance. Niosi and Bas (2001) presented some evidence of knowledge spillovers in biotechnology clusters in Canada. The authors stated that knowledge spillovers depended on the amount of knowledge produced by private companies and public institutions. The geographical proximity encourages processes of cooperation, collective learning, informal and tacit knowledge transfers. Firms operating in a particular socio-geographical entity form integrated supply chains, clusters of subcontractors, also share certain local labour resources and knowledge infrastructure of public and private research institutions. This tends to form the endogenous basis for knowledge diffuse via communication. The common base of knowledge across the firms of a regional cluster and local social endowments indicate the cumulative nature of cluster competence.

Competence at the individual, organisational or cluster level refers to the stock of knowledge accumulated by individuals or used by groups of individuals in activities of an organisation. Organisational competence confers the absorptive capacity of a firm. According to Cohen and Levinthal (1990), absorptive capacity is the ability to acquire, communicate or transmit information across units and to individuals of an organisation and the ability to assimilate and exploit external knowledge in organisational learning and performance.

1.2. Transferability of information in the cluster and differentiated competences

Organisations involved in the cluster are in constant communication with the partner organisations as well as other actors in the external environment. The capability of an organisation to integrate externally originated information into knowledge-creation activities depends on the type of information acquired, as well as the organization's technological capability and absorptive capacity (Lis & Rozkwitalska, 2020). Different authors provided different approaches to the absorption capacity concept (Cohen & Levinthal, 1990; Camison & Fores, 2010; Lane & Lubatkin, 1998). The absorption model proposed by Cohen and Levinthal involves the absorption and integration of knowledge that is valuable and available in the organisational environment. The relative absorptive capacity model, introduced by Lane and Lubatkin, considers the mechanism of knowledge transfer (Camison & Fores, 2010; Lane & Lubatkin, 1998). Knowledge resides in the mind of an individual and acquires meaning in the context of an organisation. When an organisation accepts knowledge, the sender–recipient connection operates, with one organisation as the sender and the other as the recipient. The organisation's capability to acquire, assimilate and apply knowledge, and the ability of an organisation to integrate external knowledge depend on the compatibility of knowledge processing and application systems operating in organisations of the knowledge provider and recipient (Lane & Lubatkin, 1998; Świadek, 2015). It is considered that knowledge absorption is not only about the processes and routines of knowledge acquisition and transfer within an organisation, but also about the organisation's compatibility of knowledge systems or competence. While firms hold internally developed systems and routines designed to facilitate the acceptance of externally originated knowledge, such systems are relatively coherent and contextual, and reflect exogenous or institutional clauses. Firms participating in the cluster share conditions and institutional power (the environment), such as business regulatory regime, employment regulations, legal requirements that have an impact on business transactions; as a result, there is an increasing compatibility between absorption capacities and knowledge transfer capabilities within companies operating in a territorial cluster (Tallman et al., 2004).

Proposition 1: The dissemination of knowledge within cluster firms depends on the proximity of organisation's competence.

The capability to assimilate new knowledge depends on the learning ability of an organisation. Innovative organisations acquire specific knowledge resources and skills that are related to the arrangement of recognition and cognition of incoming information. Diffusion of new knowledge within clusters of innovative organisations is likely to be more effective than the dissemination of information across geographically related clusters of organisations.

Proposition 2: The dissemination of knowledge within cluster firms depends on specific features of the organisations, such as being an innovative high-tech industrial company.

Internal processes of knowledge integration and learning depend on the nature of the incoming information. General information about a cluster partner organisation usually does not contain complex and sophisticated technological knowledge. Receiving and transmitting this information does not require specialised capabilities or expertise of those individuals to whom the information is provided. An effective management of general externally originated information requires background knowledge of shared language and symbols, knowledge of internal communication system, and also an inter-organisational relationship mechanism. Significant and confidential information provided to a cluster partner organisation usually includes substantive knowledge of a competitor's product or innovative performance. Effective communication, assimilation and exploitation of such information require complementary expertise within the recipient organisation. The capacity to absorb specialised information can be facilitated by the capability to manage flows of general information, e. g. as described by

Cohen and Levinthal, the “knowledge of who knows what, who can help with what problem or who can exploit new information” (Cohen & Levinthal, 1990, p. 133). Also, the capacity to absorb confidential information can be enhanced by a close relationship with a cluster partner. The capacity to absorb information containing technical knowledge of product or process innovation could be enabled by individuals possessing particular expertise sufficient for the communication with external sources of knowledge. The ability to integrate such information into the organisation's activity and the capacity to assimilate and utilise it depends on the competence diversity across individuals communicating knowledge-based information. The overlap of knowledge or competence among individuals receiving and transmitting technical information is required for effective communication.

Proposition 3: The access to general and selected information about cluster partners is related to the dissemination of new knowledge within the cluster companies.

2. Research methods

The article reports the outcomes of the quantitative study, which is a section of larger research concentrating on the analysis regarding the level of development of cooperative relationships in localised cooperation networks on the example of cluster and park structures. The current study aims to answer the following research question: What set of competencies of cooperating companies allows access to information and knowledge in cluster organisations and technology parks? As for the theoretical basis of the research, the authors predict that the competence proximity has an impact on the access to knowledge in cluster and park structures (Propositions 1 and 3) and this access is better for companies with high competences (Proposition 2). In this study, the competence proximity is understood as a similarity of structured and dynamic competence systems, both in terms of the scope of competence (CPs) and the level of competence development (CPl) (Lis, 2018, 2019).

The research was carried out in two groups of entities: cluster and park structures functioning in Poland. The study of cluster organisations was conducted in 2017, in four purposefully selected cluster organisations operating in Poland: in two cluster organisations representing the ICT industry (the Mazovia Cluster ICT [MC ICT] and the Interizon: the Pomeranian Region ICT Cluster) and two from the metal industry (the Metal Cluster of the Lubuskie Province [MCLP] and the Metal Working Eastern Cluster [MWEC]). The research sample consisted of 132 cluster enterprises: 51 from metal cluster organisations (38 from MWEC and 13 from MCLP) and 81 from ICT cluster organisations (45 from MC ICT and 36 from the Interizon). In the second group, the study was conducted in 2019, in three parks: the Pomeranian Science and Technology Park Gdynia [PSTPG], the Gdańsk Science and Technology Park [GSTP] and the Bydgoszcz Industrial and Technological Park [BITP]. The research covered 137 park tenants: 81 in PSTPG, 39 in GSTP and 17 in BITP.

The primary method of data collection was a survey questionnaire. The interviewees were the owners, top managers or specialists of the companies who had the most comprehensive and accurate knowledge about the realities of their company functioning in cluster organisations or technology parks. The questionnaire referred to the following topics: 1) the competence proximity in terms of the scope of competences [CPs]; 2) the competence proximity in terms of the level of competence development [CPl]; 3) the access to information and knowledge [AIK] (Table 2). With regard to the competence proximity in terms of the scope of competences [CPs], the study focused on three cases: the cooperation based on the same (or very similar) [CPs1], different but complementary [CPs2] and a very different [CPs3] set of partner competences. The competence proximity in terms of the level of the competence development [CPl] was assessed in relation to the level of competence of other companies. In turn, access to information and knowledge [AIK] included various types of resources, ranging from general [AIK1] and detailed [AIK2] information, through priority in obtaining relevant information about the environment [AIK3], to confidential information [AIK4] and knowledge [AIK5]. Data analysis was conducted using the interdependence of variables (with using Kendall's tau-b coefficient, Cramer's V), ANOVA, and logistic regression.

3. Results

3.1. Competence proximity

The research conducted in the group of cluster organisations shows that if cluster enterprises decided to cooperate with other cluster members, they chose mainly those enterprises that had the same or very similar scope of competence [CPs1], which means that they operated in the same industries and represented a similar business profile. Cooperation with enterprises

Tab. 2. Variables in the study

Competence proximity in terms of the scope of competences [CPs]	
CPs1	Our company works with cluster companies/park tenants that have the same or very similar competence (belong to the same industry, have a similar business profile)
CPs2	Our company works with cluster companies/park tenants that have expertise in a different field to ours (they belong to the same industry, and their competencies are complementary to ours)
CPs3	Our company works with cluster companies/park tenants that have completely different competences (they belong to other industries)
Likert scale (1-5): Definitely not (1) Rather not (2) Hard to say (3) Rather yes (4) Definitely yes (5)	
Competence proximity in terms of the level of competence development [CPl]	
In the cluster/park, we cooperate primarily with companies whose level of development (technology, knowledge, quality of staff) is: 1. Much lower than the level represented by our company 2. Lower than the level represented by our company 3. Similar to the level represented by our company 4. Higher than the level represented by our company 5. Much higher than the level represented by our company 6. None of the above because we do not cooperate with cluster companies/park tenants	
Access to information and knowledge [AIK]	
AIK1	One of the effects of joining the cluster/location in the park is that my company has gained access to a wide variety of information (albeit general information)
AIK2	One of the effects of joining the cluster/location in the park is that my company has gained access to selected information, fully tailored to the profile and needs of my business
AIK3	One of the effects of joining the cluster/location in the park is that my company has gained priority in receiving important information about changes in the external environment
AIK4	One of the effects of joining the cluster/location in the park is that my company is less worried about sharing certain confidential information with selected cluster companies
AIK5	One of the effects of joining the cluster/location in the park is that my company, together with other selected cluster companies/park tenants, takes part in processes of creating new knowledge (through working groups, project groups etc.)
Likert scale (1-5): Definitely not (1) Rather not (2) Hard to say (3) Rather yes (4) Definitely yes (5)	

from the same industry, but with complementary competences was slightly less frequently established [CPs2]. In turn, the least popular in the surveyed cluster organisations was the cooperation of enterprises with a completely different scope of competences and belonging to other sectors industries [CPs3] (Table 3). In the three discussed cases — the cooperation of enterprises with the same (or very similar), different (but complementary) and completely different scope of competences — the average was increasingly lower: from 2.8 points to 2.6 points up to 2.3 points. The above analysis completes the dominant value. To the question about the cooperation based on the same or very similar scope of competences, the most frequently chosen answer was No 4 (moderately positive), while to the questions about both a different and completely different set of competences, it was the answer No 1 (definitely negative).

The study shows that about 40% of cluster enterprises gave a moderate or definitely positive answer to the question about cooperation with enterprises with the same (or very similar) scope of competences, while a different or completely different scope of competences was the basis for cooperation for, respectively, approx. 30% and approx. 17% of respondents. It should be noted, however, that in all three cases moderate or extremely negative votes prevailed (i.e., more than 42% of respondents did not cooperate with cluster enterprises with the same or similar scope of competences, almost 50% did not cooperate with enterprises with a different yet complementary scope of competences, while the majority, over 61%, did not develop cross-sectoral cooperation based on a completely different scope of competences). This may indicate that a large group of cluster enterprises has not entered into any cooperation within the cluster organisation, regardless of competencies of the partners.

Regarding competence proximity in terms of the level of competence development [CPl], the study shows that enterprises in the analysed cluster organisations cooperated primarily with enterprises with a similar (to the level presented by their own organisation) level of competence development — the answer (No 3) was given by almost half of the respondents.

Tab. 3. Competence proximity [CPs] in terms of the scope of competences in cluster organisations and technology parks (N=132, 137)

Variables	Cluster organisations						Technology parks					
	Min	Max	Mean	Std. Dev.	Median	Mode	Min	Max	Mean	Std. Dev.	Median	Mode
CPs1	1	5	2.80	1.36	3	4	1	5	2.78	1.21	3	2
CPs2	1	5	2.60	1.24	3	1	1	5	2.85	1.21	3	2
CPs3	1	5	2.27	1.16	2	1	1	5	2.93	1.28	3	3
CPl	1	6	3.88	1.42	3	3	1	6	3.26	0.83	3	3

This is also confirmed by the mean value (3.9). For over 15% of enterprises, participation in the cluster organisation was an opportunity to establish cooperation with enterprises with a higher level of competence development. A relatively high percentage of respondents admitted that they did not cooperate with other cluster enterprises at all (over 27%) (hence, they were unable to answer the question regarding the level of competence development of their cluster partners).

The cooperation in the surveyed parks was slightly different than in cluster organisations considering the scope of tenant competence. The differences in the answers in the three analysed categories [CPs1–CPs3] were not as pronounced as in the case of cluster organisations. The mean value was between 2.8 and 2.9 (Table 3). Positive answers were at a level slightly above 30%, while negative concerned more than 40% of respondents in each of the three categories. In turn, a relatively large (compared to the results obtained for cluster organisations) part of the respondents (16%) indicated an extremely positive response regarding the cooperation with enterprises with completely a different scope of competences.

Comparing the answers regarding the level of competence development obtained in the group of technology parks and cluster organisations, a slightly lower result was obtained (the mean at the level of 3.3). About 60% of respondents representing the surveyed parks admitted that they cooperated with enterprises with a similar level of competence development. In turn, in the case of over 28% of respondents, their cooperation partners were companies with higher or much higher competences. Extremely low (less than 1%) was the share of enterprises that admitted not cooperating with other park tenants at all.

3.2. Access to information and knowledge

The analysis included access to information and knowledge [AIK] of entities grouped in cluster organisations and technology parks, which is closely related to the development of competence proximity in terms of the level of competence development. In the group of cluster entities, the most noteworthy is the relatively high percentage of respondents who are unable to give an unambiguous answer. To four questions (AIK2–AIK5), the answer "hard to say" was the most frequent (reaching the percentage of indications at the level from about 30% to 41%). The question about wide access to various general information in the cluster organisation [AIK1] had the smallest share of undecided respondents (about 1/4). This area also received the highest evaluation by the surveyed enterprises (the average value, in this case, was 3.5 points) with the highest share of satisfied votes (the total of almost 60%) (Table 4). Results similar in terms of the mean value (approx. 3) were obtained for questions regarding the access to selected information enabling better identification of sources of missing resources [AIK2] and significant information about the environment, key from the point of view of business activity [AIK3]. Although in both areas, total positive votes outweighed the negative, differences were small. Slightly more positive votes (almost 37%) were cast for AIK3, considering both moderate and extreme answers, while AIK2 had about 34% of positive answers. The lowest mean values were achieved for last two categories: sharing confidential information reserved only for trusted partners [AIK4] (2.8) and participating in the process of creating new knowledge [AIK5] (2.95). In both cases, negative votes dominated, constituting approximately 36% and 37% of the given answers.

The study shows that park tenants located in the studied parks have the best access to general information [AIK1] (the mean value: 3.3, 47% of positive answers) and the worst to confidential information, which is reserved for trusted partners [AIK4] (the mean value: 2.5, 55% of negative answers). The means obtained for the other three variables were similar and ranged from 2.7 [AIK3&AIK 5] to 2.9 [AIK 2] (Table 4). In surveyed parks, as in cluster organisations,

Tab. 4. Access to information and knowledge [AIK] in cluster organisations and technology parks (N=132, 137)

Variables	Cluster organisations						Technology parks					
	Min	Max	Mean	Std. Dev.	Median	Mode	Min	Max	Mean	Std. Dev.	Median	Mode
AIK1	1	5	3.52	1.11	4	4	1	5	3.26	1.00	3	4
AIK2	1	5	3.09	1.10	3	3	1	5	2.89	0.90	3	3
AIK3	1	5	3.02	1.06	3	3	1	5	2.74	0.94	3	2
AIK4	1	5	2.76	1.04	3	3	1	5	2.49	1.10	2	2
AIK5	1	5	2.95	1.20	3	3	1	5	2.74	1.18	3	3

a large share of respondents could not provide an unequivocal answer on the access to information and knowledge in the park (it ranged from approx. 24% to over 47%).

3.3. Relationship between the competence proximity and access to information and knowledge

In the case of competence proximity in terms of the scope of competences, the cause-and-effect relationship can be logically assumed, i.e., it is the cooperation of entities with a given set of competences that affects access to a specific pool of information and knowledge.

The study conducted in cluster organisations shows that there were statistically significant, positive relationships between all components of the CPs and AIK constructs (Table 5). On this basis, it can be concluded that the cooperation with other cluster partners, regardless of their scope of competence, remains in a positive relationship with the access to additional pool of information (including general, selected, significant and confidential information) and knowledge.

The observed differences in the value of the correlation coefficient are small. It turned out that the more diverse the competences of the cooperating cluster entities, the weaker the correlation. The strongest positive relationships were noticed when cluster enterprises cooperated with companies with very similar scope of competences [CPs1]. The highest values of the correlation coefficient were noted for access to selected information enabling the identification of sources of missing resources [AIK2] (0.416, p≤0.001), confidential information [AIK4] (0.405, p≤0.001), and new knowledge [AIK5] (0.359, p≤0.001). Based on the obtained results, it can therefore be concluded that cluster cooperation facilitated the access to information and knowledge for associated members. The scope of competence of the partners seems to be secondary, only to a small extent determining access to the analysed pool of resources. However, with the increase in the competence distance of partners, this access could become more and more difficult.

Slightly different results were obtained in the group of park tenants. Here, access to information and knowledge [AIK] is more determined by the scope of competences of the partners [CPs]. Entities that cooperated with enterprises with the same (or very similar) [CPs1] as well as different (but complementary) [CPs2] scope of competence had better access to the analysed resources (Table 5). In the case of cooperation based on the same or very similar set of competences [CPs1], the entities involved in this cooperation received access to all types of distinguished resources ([AIK1]–[AIK5]). Interestingly, the value of the correlation coefficient is the lowest in the case of the most easily available general information [AIK1] (0.157), and one of the highest in the case of the most difficult resource — new knowledge [AIK5] (0.408). In the case of cooperation based on a different but complementary set of competencies [CPs2], correlations occurred with almost all compo-

Tab. 5. The results of the correlation analysis in cluster organisations and technology parks: [CPs] - [AIK] (N=132, 137)

CPs	Cc/p	Cluster organisations					Technology parks				
		AIK1	AIK2	AIK3	AIK4	AIK5	AIK1	AIK2	AIK3	AIK4	AIK5
CPs1	Cc	0.323**	0.416**	0.333**	0.405**	0.359**	0.157*	0.415**	0.211**	0.258**	0.408**
	p	0.000	0.000	0.000	0.000	0.000	0.028	0.000	0.003	0.000	0.000
CPs2	Cc	0.269**	0.328**	0.244**	0.264**	0.222**	0.133	0.306**	0.273**	0.376**	0.375**
	p	0.000	0.000	0.001	0.000	0.002	0.061	0.000	0.000	0.000	0.000
CPs3	Cc	0.194**	0.277**	0.305**	0.170*	0.153*	0.208**	0.084	0.124	0.073	-0.048
	p	0.008	0.000	0.000	0.020	0.034	0.003	0.242	0.082	0.299	0.492

nents of the AIK construct, except for general information [AIK1]. Also, in this case, the value of the correlation coefficient for new knowledge [AIK5] was very high (0.375), similar to access to confidential information [AIK4] (0.376). Research shows that the cooperation of entities with completely different competences [CPs3] does not determine access to most of the analysed types of information and knowledge. The only relationship that emerged in this case was access to general information [AIK1] (0.208).

The differences in access to knowledge and information in groups with various sets of competences were additionally evaluated by performing the analysis of variance of data covering both cluster companies and park tenants. The results of the variance analysis showed that access to both general and specific information as well as involvement in knowledge dissemination activities differed significantly between various groups of collaborating companies (Table 6).

Compared to the dissemination of information and knowledge within the group of different competence, in cooperation with companies with a similar field of expertise, partners gain more access to a variety of information, as well as are more willing to participate in knowledge dissemination processes.

The mean value of information and knowledge availability to cluster companies is interpreted by a measurement scale of the variable (1 — definitely no, 5 — definitely yes). Information availability and knowledge dissemination opportunities are more negatively evaluated by cooperating companies with different competencies, the mean value for all variables is barely 3; and among companies with similar or identical competences, the mean for all variables of information and knowledge dissemination is statistically significantly higher, and for most variables reaches a rank value consistent with a positive rating. In all enterprise groups, the mean value is lower for variables of more complex information or knowledge dissemination.

In the case of competence proximity in terms of the level of competence development, it is difficult to logically determine the sides of a causal relationship. The correlation analysis conducted between competence proximity in terms of the level of competence development [CPl] and access to information and knowledge [AIK] in the surveyed cluster organisations shows a statistically significant relationship between the mentioned variables. The differences are very small — the highest value of the correlation coefficient was in the case of access to general information [AIK1] (0.324), and the lowest in the case of access to confidential information [AIK3] (0.274) (Table 7). Therefore, it can be concluded that there is a moderate relationship between the level of competence development [CPl] of cluster enterprises and the access to all distinguished information and knowledge resources [AIK] in cluster organisations.

In the case of surveyed parks, a statistically significant relationship between the analysed variables [CPl] and [AIK] occurred in relation to access to selected information [AIK2] (0.299) and the priority in access to significant information on the environment [AIK3] (0.277) as well as access to general information [AIK1] (0.259). However, there was no correlation with regard to access to these most difficult resources, namely,

Tab. 6. Results of the analysis of variance in cluster organisations and technology parks: [CPs] - [AIK] (N=269)

AIK	Competence of collaborating organisations							
	CPs1(1-2), (N=118) (1)		CPs1(3), (N=53) (2)		CPs1(4-5), (N=98) (3)		Total (N=269)	
	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
AIK1	3.02	1.18	3.51	0.99	3.76	0.77	3.38	1.06
Parameters of ANOVA for variables (AIK1), (CPs1) F=14.82, p=0.000<0.01. The mean difference for the competence groups 1 and 2; 1 and 3 is significant at the 0.01 level								
AIK2	2.47	0.99	3.28	0.72	3.46	0.85	2.99	1.01
Parameters of ANOVA for variables (AIK2), (CPs1) F=36.63, p=0.000<0.01. The mean difference for the competence groups 1 and 2; 1 and 3 is significant at the 0.01 level								
AIK3	2.49	1.00	3.21	0.93	3.16	0.90	2.88	1.01
Parameters of ANOVA for variables (AIK3), (CPs1) F=17.35, p=0.000<0.01. The mean difference for the competence groups 1 and 2; 1 and 3 is significant at the 0.01 level								
AIK4	2.19	0.97	3.00	1.04	2.95	1.04	2.62	1.08
Parameters of ANOVA for variables (AIK4), (CPs1) F=19.73, p=0.000<0.01. The mean difference for the competence groups 1 and 2; 1 and 3 is significant at the 0.01 level								
AIK5	2.29	1.09	3.13	1.00	3.36	1.13	2.84	1.20
Parameters of ANOVA for variables (AIK5), (CPs1) F=28.12, p=0.000<0.01. The mean difference for the competence groups 1 and 2; 1 and 3 is significant at the 0.01 level								

Tab. 7. The results of the correlation analysis in cluster organisations and technology parks: [CPI] - [AIK] (N=132, 137)

Access to information and knowledge [AIK]	Cluster organisations		Technology parks	
	Cramer's V	p	Cramer's V	p
AIK1	0.324	p<0.0001	0.259	0.012
AIK2	0.303	0.001	0.299	0.000
AIK3	0.322	p<0.0001	0.277	0.003
AIK4	0.274	0.008	0.240	0.048
AIK5	0.301	0.001	0.214	0.197

Tab. 8. Results of the analysis of variance in cluster organisations and technology parks: [CPI] - [AIK] (N=230)

AIK	Competence proximity of collaborating enterprises in terms of the level of development							
	CPl(1-2) (N=26) (1)		CPl(3) (N=145) (2)		CPI(4-5) (N=59) (3)		Total (N=230)	
	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
AIK1	2.88	1.40	3.57	0.92	3.32	1.06	3.43	1.04
Parameters of ANOVA for variables (AIK1), (CPI) F=5.49, p=0.005<0.01. The mean difference for the competence groups 1 and 2 is significant at the 0.01 level								
AIK2	2.46	1.17	3.28	0.92	2.85	0.91	3.07	0.99
Parameters of ANOVA for variables (AIK2), (CPI) F=10.35, p=0.000<0.01. The mean difference for the competence groups 1 and 2; 2 and 3 is significant at the 0.01 level								
AIK3	2.50	1.17	2.99	0.90	3.02	1.11	2.94	1.00
Parameters of ANOVA for variables (AIK3), (CPI) F=2.97, p=0.054>0.05. Mean differences for competence groups are not statistically significant								
AIK4	2.23	1.37	2.71	1.04	2.76	1.09	2.67	1.10
Parameters of ANOVA for variables (AIK4), (CPI) F=2.39, p=0.094>0.05. Mean differences for competence groups are not statistically significant								
AIK5	2.42	1.42	3.05	1.15	2.80	1.21	2.91	1.21
Parameters of ANOVA for variables (AIK5), (CPI) F=3.35, p=0.037<0.05. The mean difference for the competence groups 1 and 2 is significant at the 0.05 level								

confidential information [AIK4] and knowledge [AIK5].

The analysis of variance was used to assess differences in information and knowledge dissemination across enterprise groups by the level of competence development. The analysed sample included data obtained in both groups (cluster organisations and technology parks) (Table 8).

The results of the analysis of variance showed that the dissemination of information and knowledge was rated the highest in the group of cooperating companies of similar development as compared to groups of companies of different level of development. However, the mean value for almost all variables was less than 3or slightly above, i.e. the value was consistent with the average rating. The differences of information and knowledge dissemination in various enterprise clusters were statistically significant for the variables of access to general and selective information, as well as for the variable of access to new knowledge. Access to a variety of general information and selective information and knowledge was significantly higher in groups of companies with a similar level of competence development.

3.4. Dissemination of knowledge

Cooperating companies that have the same or similar competence in terms of the scope of the competence are more active in knowledge creation activities. Companies that collaborate with other cluster companies of similar expertise are statistically significantly more frequently involved in collaborative processes of new knowledge creation. 54.6% of the companies within the group that have reported cooperating with other cluster partners that have the same competence indicated their involvement in knowledge creation processes. In the group of companies that do not cooperate with other cluster companies of the same or similar competence, merely 19.3% reported their participation in knowledge creation activities together with other cluster companies.

The collected data support the proposition that the dissemination of new knowledge within cluster firms depends on the proximity of an organisation's competence. Differences of participating in knowledge dissemination activity are related to differences in partnerships in terms of the competence scope proximity. Pearson's chi-square value is 35.47, and the observed significance level is $p<0.01$, which confirms the hypothesis that the engagement in knowledge creation activities depends on the competence proximity of cooperating firms in terms of the competence scope (Table 9).

The strength of the association was moderate between variables of companies participating in a partnership with the companies of proximal competence in terms of the scope of competence, and participating in knowledge dissemination together with other cluster companies (Cramer's V = 0.364, $p<0.01$).

The collected data did not support the proposition that the dissemination of knowledge within cluster firms depended on the proximity of organisational competence in terms of the level of development (the level of development of technology, knowledge, and the quality of staff). 23.1% of the companies within the group that reported the cooperation primarily with other cluster partners having a lower level of development (in terms of technology, knowledge, quality of staff) indicated their involvement in knowledge creation processes. Cooperation in knowledge creation processes was noted by 37.5% and 35.6% of the respondents, respectively, representing companies that cooperate with other companies having a similar and higher level of development (a total of 35.4% of all companies were involved in collaborative knowledge creation activities). Differences in the frequency of participation in knowledge creation activities among different groups of companies are not statistically significant (the significance of the chi-square test statistic was $p=0.367>0.05$). The behaviour of organisations in relation to cooperative activities for the development and dissemination of knowledge is independent of the differences between the cooperating organisations in terms of their level of competence development.

The crosstabs analysis of the research data showed that the differences in the frequency of participation in knowledge creation activities among the regional cluster and high technology (technology parks) enterprise groups were not statistically significant (the significance of the chi-square test statistic was $p=0.607>0.05$). The involvement of organisations in knowledge creation activities was reported by 33.6% of representatives of regional cluster companies and 30.7% of enterprises belonging to high-tech groups (technology parks). The second proposition that the dissemination of new knowledge within a group of cluster firms depends on specific features of the organizations, such as being an innovative high-tech industrial company, was not supported by our research.

A logistic regression analysis was performed to identify the impact of information dissemination among cluster companies and the effect made by the proximity of competence of cooperating organisations on the likelihood that cluster companies participated in knowledge creation activities. To evaluate the impact of different factors determining the involvement of organisations in knowledge creation and dissemination activities among the companies participating in the cluster, different models for the sample companies, cluster organisations and innovative parks companies were computed (Table 10).

Logistic regression models are statistically significant, $p<0.01$. The first model of the total sample data explained (Nagelkerke R2) 37.50% of the variance in cluster companies' involvement in knowledge creation activities, while the result for the second model of the regional cluster sample scored 50.7%, and the third model of high tech parks — 33.2%, and, respectively, correctly classified 76.9%, 78.5%, and 77.9% of cases in

Tab. 9. Results of the crosstabs analysis: [CPs] - [AIK6] (N=268)

AIK		CPs1 (1-3)	CPs1 (4-5)	Total
AIK6: definitely not, rather not, hard to say	Count	138	44	182
	% within work with other companies that have/do not have the same competence	80.70%	45.40%	67.90%
	% of total	51.50%	16.40%	67.90%
AIK6: rather yes, definitely yes	Count	33	53	86
	% within work with other companies that have/do not have the same competence	19.30%	54.60%	32.10%
	% of total	12.30%	19.80%	32.10%
Total	Count	171	97	268
	% of total	63.80%	36.20%	100.00%

Tab. 10. Parameters of the logistic regression models

Variables	Total sample, N=229			Cluster organisation sample, N=93			Park sample, N=136		
	B	Sig.	Exp(B)	B	Sig.	Exp(B)	B	Sig.	Exp(B)
AIK1	0.254	0.207	1.289	1.004	0.031	2.729	0.094	0.703	1.099
AIK2	0.203	0.378	1.225	-0.484	0.226	0.616	0.515	0.103	1.674
AIK3	0.317	0.13	1.373	0.812	0.045	2.253	0.128	0.633	1.137
AIK4	0.612	0.001	1.844	0.905	0.026	2.473	0.534	0.015	1.705
CPI_1_2_3	0.026	0.932	1.026	0.615	0.307	1.849	-0.11	0.777	0.895
CPs1_1_2_3	0.711	0.001	2.037	0.755	0.04	2.127	0.771	0.004	2.162
Constant	-6.466	0.000	0.002	-11.107	0.000	0.000	-5.825	0.000	0.003
Logistic regression results:									
$\chi 2(6)$, (p)	73.028, (p<0.01)			43.95, (p<0.01)			36.524, (p<0.01)		
Nagelkerke R^2	0.375			0.507			0.332		
Predicted percentage correct	76.9			78.5			77.9		

different samples. The variable of dissemination of confidential information between cluster partners (AIK4) and the variable of competence of collaborating firms (CPs1, 1 — different competence among the cluster partners, 2 — neither different nor similar competence among the cluster partners, and 3 — similar competence among the cluster partners) added significantly to all three models, but the variable of access to selected information disseminated among cluster partners (AIK2) and the variable of competence of collaborating firms in terms of the level of development (CPI, 1 — partner's level of development is lower than the level of our company, 2 — partner's level of development is similar to the level of our company, and 3 — partner's level of development is higher than the level of our company) did not add significantly to either of the three.

For log regression parameter values, the likelihood that cluster firms would collaborate in knowledge production activities was calculated. For the data of the total sample, when the competence variable acquires values from 1 (cooperating firms have different competences) to 3 (collaborating firm competence is similar), and all variables of information dissemination gain the highest values (5), and the variable of the partner competence level gains the value of 2 (similar level of development), the likelihood that a firm would collaborate with cluster partners in the knowledge creation and dissemination processes increased from 0.773 to 0.934. Similarly, when the variable of dissemination of confidential information between cluster partners acquired values from 1 (it is acknowledged that cooperating companies definitely do not share confidential information) to 5 (it is acknowledged that cooperating companies definitely share confidential information), and other variables of information dissemination and partner competence gain the highest values, the likelihood that firm would collaborate with cluster partners in the knowledge creation and dissemination processes increased from 0.550 to 0.934 (Prob(AIK4(2))=0.693; Prob(AIK4(3))=0.806; Prob (AIK4(4))=0.885).

The results of the logistic regression model for the data of tech-parks show that the likelihood of access to knowledge dissemination processes in a group of clustered companies is associated with two statistically significant variables, namely, the availability of confidential information and competence of cooperating organisations. An increasing rating of access to confidential information and similar competence was associated with an increased likelihood of access to knowledge creation activities. For the data on the sample of tech-parks, when the competence variable acquired values from 1 (cooperating firms have different competences) to 3 (collaborating firm competence is similar), and all variables of information dissemination gained the highest values, and partner competence level variable gained the value of 2 (similar level of development), the likelihood that firm would collaborate with cluster partners in the knowledge creation and dissemination processes increased from 0.747 to 0.932. Similarly, when the variable of dissemination of confidential information between cluster partners acquired values from 1 to 5, and other variables of the information dissemination and partner competence gained the highest values, the likelihood that firm would collaborate with cluster partners in the knowledge creation and dissemination processes increased from 0.619 to 0.932 (Prob(AIK4(2))=0.735; Prob (AIK4(3))=0.826; Prob(AIK4(4))=0.890).

The results of the logistic regression model for the data of regional clusters show that variables of access to general information, access to information about the changes in the external environment, access to certain confidential information and the variable of competence of cooperating organisations added significantly to the model. Variables of access to general information and access to certain confidential information have the greatest influence on the variation of the dependent variable (respectively, EXP(B)=2.73 and EXP(B)=2.47). A growing rating of access to general information is associated with an increased likelihood of access to knowledge creation activities in regional clusters. For the data of the sample for regional clusters, when the variable of access to general information acquired values from 1 to 5, and all other variables of information dissemination gained the highest values, the competence level variable gained the value of 2 (a similar level of development), and the competence scope variable gained the value of 3 (similar competence), the likelihood that a firm would collaborate with cluster partners in the knowledge creation and dissemination processes increased from 0.391 to 0.973 (Prob(AIK1(2))=0.637; Prob(AIK1(3))=0.827; Prob (AIK1(4))=0.929). Similarly, when the competence variable acquired values from 1 (cooperating firms have different competences) to 3 (collaborating firm competence is similar), and all variables of information dissemination gained the highest values, and the partner competence level variable gained the value of 2 (a similar level of development), the likelihood that a firm would collaborate with cluster partners in the knowledge creation and dissemination processes increased from 0.887 to 0.973. The effect of competence proximity variable was almost the same in all three models.

Logistic regression models reflect the impact of information dissemination on the process of knowledge creation in clustered enterprise groups. A comparison of logistic regression models for regional cluster data and innovative technology park data suggests that information transfer processes and their impact on innovation and knowledge dissemination processes in regional clusters and technology parks differ significantly. Knowledge creation and dissemination processes in regional cluster companies are facilitated by the availability of different types of information, while the impact of general information and environmental information on knowledge creation processes is less significant in innovative park clusters. The collected data support the hypothesis that access to general and selected information about cluster partners is related to the dissemination of new knowledge within cluster companies.

4. Discussion of the results

The paper analysed the impact of the proximity of competencies of cluster organisations on the dissemination of information and knowledge within the cluster. The comparison of the research results on competence proximity [CP] in cluster organisations and technology parks, leads to a conclusion that companies tend to participate in joint activities primarily with enterprises similar in terms of the level of competence development [CPl] (regardless of the degree of their diversity). Considering the scope of competences [CPs], cluster entities preferred cooperation with enterprises with the same (or very similar) [CPs1] or different (but complementary) set of competences [CPs2], while park entities similarly often decided to cooperate with each of the three distinguished groups of partners (that had the same/similar, a different/complementary and completely different set of competences [CPs1]–[CPs3]).

Based on the conducted research, it can also be concluded that in cluster organisations and technology parks, better access to information and knowledge [AIK] was reported by partners with the same or very similar scope of competences [CPs1], as well as with different but complementary competences [CPs2]. It is important to note that this also included access to confidential information [AIK4] as well as to new knowledge [AIK5]. On the other hand, cooperation of companies with a too wide range of competences [CPs3] did not guarantee access to information, especially in science and technology parks. Moreover, there was a moderate relationship between the level of competence development [CPl] of enterprises representing both types of studied entities and access to information and knowledge resources [AIK] (except for access to confidential information and new knowledge in parks).

Furthermore, the research data showed that knowledge creation activities performed by cooperating cluster organisations depended on the proximity of the competencies of organisations, as well as on the nature of the information, disseminated within the cluster organisations. The capability-based theoretical perspective of organisational competence considers competence as a resource that enables various processes and capabilities of an organisation, such as the absorptive capacity — the capacity to acquire external information and exploit it for the activities of knowledge creation. Companies with proximal competence are likely to have a similar absorptive capacity, so the proximity of competence is related to more effective dissemination of information and knowledge among involved organisations. The results for the competence scope could be referenced to this state of knowledge. The results for organisational competence in terms of the proximity of the level of development were ambiguous.

Based on the research, it can be concluded that access to general information about cluster organisations and relevant information about changes in the external environment, as well as sharing of certain confidential information with a cluster partner had a significant impact on the likelihood that cluster organisations would be able to integrate external information in organisation's knowledge creation activities. This result was in line with the theory of the absorptive capacity and a gradual process of information acquisition, transfer, assimilation, application and integration within an organisation's knowledge systems. Different results of information transfer that we obtained in the group of science and technology parks reflect the idea of the relative absorptive capacity. The relative absorptive capacity model states that the capability of an organisation to integrate knowledge depends on the compatibility of the knowledge transfer and development systems used by collaborating partners. Science and technology companies are characterised by more developed processes of learning, transfer and integration of knowledge, and creation of innovations. When companies of technology parks cooperate, the transfer and assimilation of information take place in coordinated compatible structures. Therefore, the impact of general and environmental information on knowledge creation in science and technology park companies is less important than in regional cluster companies.

Conclusions

The theoretical contribution is related to the results obtained by analysing the phenomenon of knowledge dissemination in business clusters, revealing the impact of the proximity of competencies of cooperating organisations and the nature of disseminated information. This study supports the notion derived from the theoretical underpinnings that the proximity of competencies is significant for the dissemination of information and the creation of new knowledge in groups of organisations. The findings were based on the concepts of organisational competence and the absorptive capacity and added to the state-of-the-art knowledge related to the phenomenon of industrial clusters.

These empirical findings also offer some practical implications for both cluster coordinators and park managers. The identified relationships between an organisation's competence and access to information and knowledge in cluster and park structures can be helpful in their design and development. Knowledge about the most desirable set of partner competences from the point of view of transferability of knowledge can be particularly useful in setting rules for entry into cluster organisations and technology parks (criteria for selecting cluster members and park tenants). It can also be valuable when creating smaller subgroups within these organisations (task or project groups) focused on achieving specific goals.

The study has some limitations. First, a relatively small sample, both from the point of view of the number of cluster organisations and technology parks (seven organisations in total) as well as the number of respondents (269 in total). Second, a small diversity in the sample, especially since it included only Polish organisations, which limits the possibility of generalising the conclusions. Nevertheless, the sample size was sufficient to perform the planned analyses, and the applied logic of sample selection (as a differentiating criterion: the sector in the case of cluster structures and the type of park in the case of park structures) allows a thesis to be put forward regarding a wider universality of the discovered regularities. This applies especially to countries with similar innovation and cluster policies. The third limitation is the subjectivity of conducted research (results were based on the subjective responses of respondents).

Future research should focus on developing the conceptual model, in which identified relationships between organisational competence and access to knowledge and information in cluster and park structures could be studied in greater detail. This model should consider additional factors that can act as a mediator or moderator in analysed relationships (e.g. involvement of companies in cluster or park activities, their technological capability and absorptive capacity, relationships with other cluster members or park tenants). It is also necessary to improve measurement tools by using an ordinal scale for all variables, as well as conducting exploratory and confirmatory factor analysis to test the measurement model. Furthermore, to test the conceptual model (preferably using structural equation modelling), the study should be conducted in a larger, more representative sample (considering national conditions, additional sectors of the economy, a different type of cluster organisations and parks etc.).

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Quantitative assessment of working conditions in the workplace

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ABSTRACT

Indicators, different in terms of nature and grading scales, are used to recognise hazardous and harmful factors that affect human health. However, no single methodology is available for their assessment, and the variety of qualimetric assessment methods requires in-depth research, in part on optimality and efficiency. Therefore, this work aimed to conduct several scientific studies to obtain the results of the assessment in unified units of measurement, which would provide a generalised indicator of harmful factors at the workplace. The article proposes to use dependencies to assess indicators of harmful factors, considering the maximum, minimum, and optimal values as well as the shape parameter, the change of which produces various assessments in a dimensionless scale. A hierarchy analysis method was used to obtain reliable values with a small number of experts and determine the form parameter. These efforts resulted in the value of the overall index for harmful factors, which serves as grounds for decisions regarding further improvements in working conditions. The developed methodology was used to assess the safety of working conditions at a machine-building enterprise, and the results are presented in the article.

KEY WORDS

quantitative assessment, management, shape parameter, dependence, overall index

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Introduction

The quality of our life, in general, is determined by many factors, such as education, the state of healthcare, freedom of speech, and occupational safety. The national occupational safety situation is indicative of the public attitudes towards such most significant values as human life. Based on international experience, a work organisation that ignores occupational safety requirements undermines the economic efficiency of enterprises and cannot be the basis for a sustainable

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development strategy. The UN concept of "sustainable human development" considers work safety as one of the basic human needs. It is, therefore, urgent to ensure occupational safety at the stages of product design, manufacture, and operation and develop technologies that are safe for the life and health of the employees. Safe working conditions demand a constant process of their assessment, analysis and continuous management.

Occupational safety management aims to develop a system of measures that provide objective information about a managed asset, aiming to develop and adopt managerial decisions required to make it safer. Effective management requires more advanced and cost-effective methods of information collection and processing.

In practice, the assessment of working conditions is reduced to the identification of work-related harmful and dangerous factors, and the establishment of the quantitative degree of work-related health risks. To accurately predict and minimise harmful and dangerous factors, it is necessary to carry out their assessments, which must be quantified. Therefore, there is a need for research and development of modern management solutions aimed at enhancing the protection of employees from harmful factors, including the improvement of methods for assessing working conditions and the search for new criteria. Thus, the article aims to develop a quantitative evaluation method for the safety of working conditions.

1. Literature review

As is widely known, the process of work involves factors related to the environment and processes that can affect health. However, a complete exclusion of unfavourable factors from the production environment is impossible even in industries with advanced process technologies, modern equipment, high production culture and excellent medical care. For example, mechanical engineering is characterised by a large number of work-related and occupational diseases, such as sensorineural hearing loss, vibration disease, pneumoconiosis, dust bronchitis, musculoskeletal disorders and peripheral nervous systems diseases (Suuronen et al., 2007; Azizi, 2010; Bonner, 2010). Therefore, their assessment is urgent aiming to predict and prevent harmful and dangerous production factors.

In a company, the occupational protection and risk management system is a part of the overall management system, which functions to increase the level of safety at work, to reduce, prevent and eliminate exposure to hazardous factors and to manage risks associated with hazards (Holubova, 2016).

Tabor (2018) argued that the development of health and safety management systems and the tendency to integrate them with other management systems in the company create serious requirements for assessing their effectiveness. The researcher proposed to use the Gray System Theory (GST), Simos procedure at the stage of determining the weights of individual elements pertaining to the health and safety management system, as well as the method of arithmetic mean at the stages of aggregation assessment.

The assessment, analysis and management of occupational safety risks have become a relevant problem, and given its complexity and multidimensionality, its solution is in high demand. Several publications have been devoted to the issues of risk assessment in the field of occupational health and safety (Ramos et al., 2020; Rosa et al., 2015; Tchiehe & Gauthier, 2017; Silva et al., 2019; Nordlöf et al., 2017; Kim et al., 2019; Bianchini et al., 2017; Barb & Fita, 2019; Darabont et al., 2017; Saracino et al., 2016). An analysis of scientific papers showed the lack a sound mathematical apparatus, expert decisions, and a single approach to hazard assessment. Regression models used for a mathematical analysis are ineffective, and scientific approaches are organisational in nature.

Zavadskas and Turskis used the multicriteria ARAS method to assess the microclimate in an office building. The ARAS method is based on quantitative measurements and the theory of practicality. In this method, the value of the auxiliary function determines the relative effectiveness of the alternative compared to other alternatives. This auxiliary function is directly proportional to the relative result of the criteria values and the weight significance of the criterion in question. The usefulness of using an alternative is determined by comparing the option with the ideally best alternative.

Ginevičius et al. (2015) studied features pertaining to the assessment of quality management systems. The researchers developed a set of dependencies between individual indicators of the process quality and their values on a dimensionless scale. This combination allowed a quantitative assessment of the quality of processes and permitted to consider the diversity of indicators and the significance of processes.

Trisch et al. (2016) proposed to assess the quality management system at the operational stage by assessing a set of interrelated processes, that is, to combine assessments of various processes in one data set and to assess it as a whole. According to researchers, the procedure increases the amount of information about the assessment of the quality of the system as a set of processes, which allows evaluating the entire system with greater objectivity and reliability. Aiming to solve this problem, the authors proposed statistical methods with non-parametric statistics, since non-parametric statistical data do not require to know the law of distribution of random values, but more statistical data that can be provided by combining assessments of quality processes.

Ginevičius and Podvezko (2007, 2008) used multicriteria methods for quantitative assessment of the quality of processes, which allow bringing their indicators to one dimension. The authors confirmed the SAW (simple additive weighing) method as the simplest and most widely applicable. This method aims to determine individual quality indicators and the values of their weights and then determine the integral value.

The multicriteria TOPSIS assessment method is a technique for order of preference by similarity to ideal solution (Ginevičius & Podviezko, 2013; Ginevičius et al., 2014). The main idea of the method is to separately assess the remoteness of indicators from the initially determined ideal and anti-ideal points, and then to convert these two indicators into one general assessment (Šimelytė & Antanavičienė, 2013; Beinoraitė & Drejeris, 2014).

Different authors (Krivka, 2014; Brauers et al., 2014; Hashemkhani et al., 2015) used such multicriteria methods as PROMETHEE (preference ranking organisation method for enrichment evaluation), MOORA (multi-objective optimisation method by ratio analysis), WASPAS (weighted aggregated sum product assessment) to assess various social objects, including processes in organisations.

The analysed assessment methods have been used to assess the quality of products and various processes of the quality management system. Therefore, the literature review confirmed the relevance of the study aimed at developing methods for assessing the safety of working conditions in the workplace.

2. Research methods

The definition of the overall index of harmful factors in the workplace is associated with obtaining a single assessment that quantitatively expresses safety through its individual indicators. The following must be done to find it:

- to establish the characteristics to be assessed;
- to determine the frequency of monitoring and measurement of indicators of harmful factors;
- to determine the maximum and minimum acceptable value of each harmful factor indicator;
- to define the optimal value of each harmful factor indicator;
- depending on the optimal value of a single indicator, to determine the group, to which this indicator of harmful factors belongs:
  - a group of indicators of harmful factors, in which the optimal (the best) value is directed to the lower limit of acceptable values, in accordance with regulatory requirements, e. g., vibration, noise etc. In this case, the less these indicators, the better;
  - a group of indicators of harmful factors, in which the optimal (the best) value is directed towards the middle of the range of acceptable values, according to regulatory requirements, e. g., air temperature.

Considering that different groups of indicators of harmful factors have different optimal values, the authors of this article propose building dependencies for each group, which would allow unifying the system of dependencies to determine the assessment of any indicator. This type of dependency was first used by Dieringer (1980) for the optimisation of technological processes and by Gorbenko (2013) for the assessment of quality management systems. However, the authors of this article believe that their application in terms of determining the shape parameter is not perfect, which is the most important factor in the optimality of their application in practice. Below, this type of dependency is examined and applied to evaluate indicators of harmful factors.

The dependence is proposed to obtain an assessment of indicators of harmful factors on a dimensionless scale (from 0 to 1):

$$S_q = \begin{cases} 0 & q_i \le q_{i\,min} \\ \left[\dfrac{q_i - q_{i\,min}}{q_{i\,max} - q_{i\,min}}\right]^{(r)} & q_{i\,min} < q_i < q_{i\,max} \\ 1 & q_i \ge q_{i\,max} \end{cases} \qquad (1)$$

where q_i — the actual value of the harmful factor indicator; q_{imin} — minimum value of the harmful factor indicator; q_{imax} — maximum value of the harmful factor indicator; r — shape parameter that changes the shape of the dependency.

If the shape parameter r is changed from 0.1 to unity in increments of 0.2, then the dependencies will be curved upward, and if the shape parameter is changed from 1 to nine in increments of 2, then the dependence will be concave down (Fig. 1).

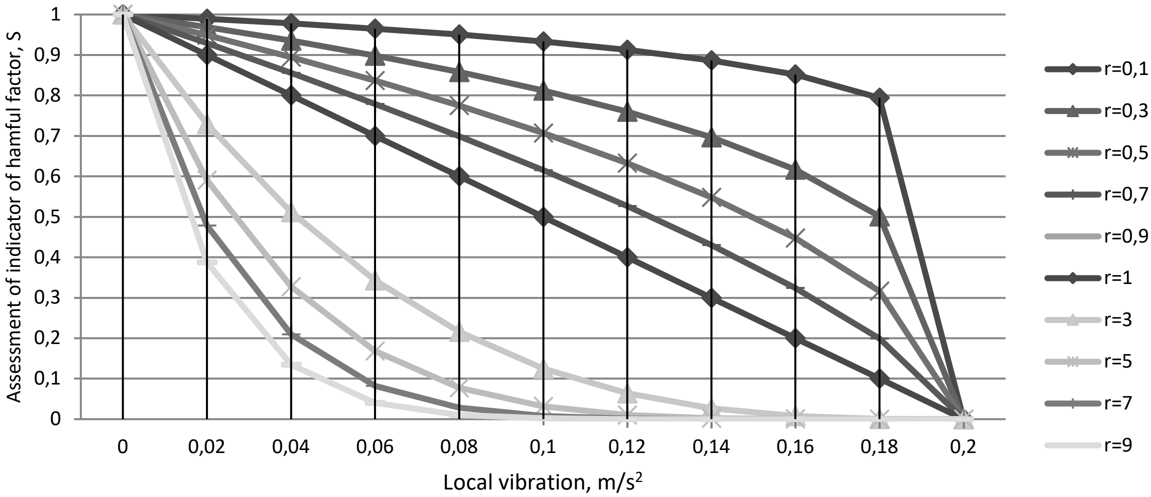

Fig. 1. Indicators of harmful factors, in which the optimal (the best) value is directed to the lower limit of the tolerance field, e. g., local vibration, no more than 0.2 m/s2

If the optimal (the best) harmful factor indicator is the middle of the limit of acceptable values, then the dependence will look as follows:

$$S_q = \begin{cases} \left[\dfrac{q_i - q_{i\,min}}{t_i - q_{i\,min}}\right]^{(r)} & q_{i\,min} \le q_i \le t_i \\ \left[\dfrac{q_i - q_{i\,max}}{t_i - q_{i\,max}}\right]^{(r)} & t_i < q_i \le q_{i\,max} \\ 0 & q_{i\,min} > q_i > q_{i\,max} \end{cases} \qquad (2)$$

where t_i — the middle of the limits of permissible values.

In this case, the dependency system will have the form shown in Fig. 2.

The result is a system of dependencies that allows obtaining assessments of indicators of harmful factors on a dimensionless scale. Next, the positive aspects of the dependency system should be considered. Firstly, these dependencies have a shape parameter that allows to change its shape and to choose the most suitable option for each indicator. Secondly, the proposed dependencies consider the maximum, minimum, and optimal value of the harmful factor indicator, as well as do not require manual adjustment of the rating scales. Thirdly, the simplicity of the models allows putting them into practice without special knowledge, which is particularly valuable when assessing the indicators of harmful factors in the workplace.

Aiming to transfer single different-sized indicators of harmful factors into a single dimensionless scale and to find a quantitative assessment, it is necessary to determine the dependence. The choice of one of ten dependencies is influenced by many factors,

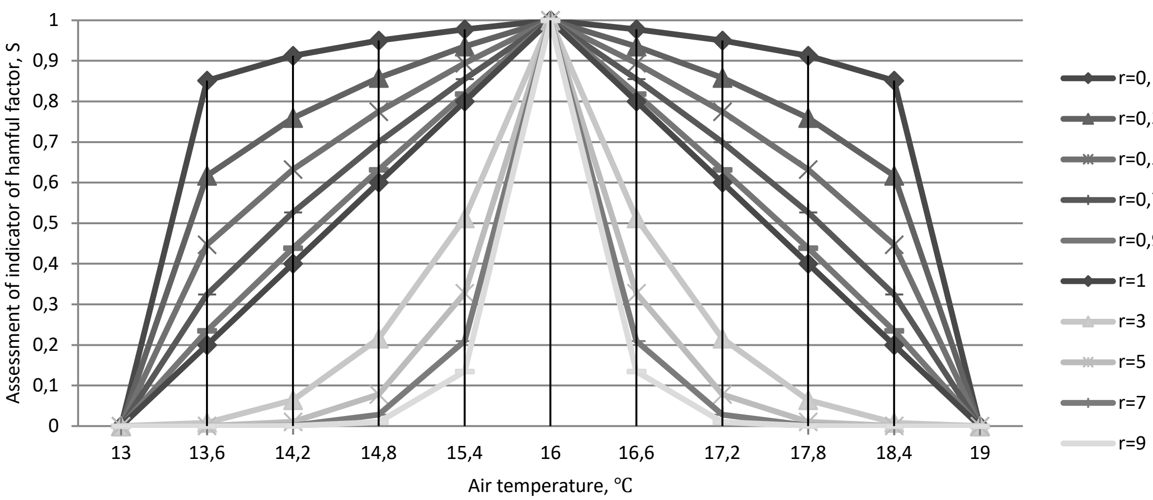

Fig. 2. Optimal (the best) harmful factor indicator goes to the middle of the range of acceptable values (air temperature)

including the degree of influence on employee health, the complexity and specifics of the work, the period of the year etc. It is impossible to quantify this choice since each indicator has its characteristics and allowable regulatory requirements, which change over time. Therefore, it is necessary to turn to the theory of expert assessments, where decision-making is understood as the choice of an alternative from the set based on an analysis of factors or criteria.

The hierarchy analysis method (Saaty, 1980; Saaty, 2005) based on determining the weight of objects using paired comparisons is proposed for the selection of the necessary dependence for assessing a specific process. This method aims to present the problem in the form of a hierarchy, where the problem itself is on the first level (substantiation of the dependence choice) with the most important harmful factors from the experts' point of view placed on the second and the third hosting the parameters of the forms that should be assessed by characteristics of the second level. The criteria are compared in pairs regarding the impact on the final goal. The comparison uses the rating scale proposed by the author of the method. Based on the results of paired comparisons, a square matrix is constructed:

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{2n} \\ a_{31} & a_{32} & a_{33} & a_{3n} \\ a_{n1} & a_{n2} & a_{n3} & a_{nn} \end{pmatrix} \quad (3)$$

Similar matrices are constructed for paired comparisons at the second level and with respect to the common goal at the first level and the third level with respect to the criteria of the second level. The general significance of the solution ($X_i = \frac{a_j}{S}$, where S is the sum of the assessment vectors) is found by obtaining the components of the eigenvector of the matrix as the geometric average of the row ($a_j = \sqrt[n]{a_{11}a_{12}a_{13}a_{1n}}$). A feature of this method is the built-in criterion for the quality of work performed by the experts — the consistency index.

One of the averages (arithmetic, geometric, harmonious) can be used to find the overall index of a harmful and dangerous factor, which makes it possible to bring together individual assessments. Determining the geometric mean value will give an assessment of occupational safety zero if one of the indicators is zero, and a unit, that is, the maximum value, can be obtained only when all unit indicators are equal to one. In this case, the overall harmful factor indicator is calculated by the formula:

$$Q = \sqrt[n]{\prod_{i=1}^{n} S_{qi}} \quad (4)$$

where n — number of single harmful factor indicators; S_{qi} — the value of the i single harmful factor indicators on a dimensionless scale.

The determination of the overall index can be carried out according to the formula of the harmonic mean:

$$\frac{1}{Q} = \frac{1}{n}\sum_{i=1}^{n} \frac{1}{S_{qi}} \quad (5)$$

Also, the overall harmful factor indicator can be defined as the arithmetic mean of assessments S_{qi}:

$$Q = \frac{1}{n}\sum_{i=1}^{n} S_{qi} \quad (6)$$

Thus, the obtained value of the overall index of harmful factors provides grounds for decisions aimed at further improvement of the safety of working conditions.

3. Results and discussion

The studies were conducted at the machine-building plant to confirm the operability of the developed methodology for assessing the safety of working conditions. For assessment, harmful production factors in the foundry were examined. It was determined that microclimate (air temperature, relative humidity, air velocity, and thermal radiation intensity), noise and vibration were the main harmful production factors in the foundry.

The values of these indicators have been measured and recorded at workplaces and in the working area for 31 days. A combined device FLIR EM54 was used to measure air temperature, relative humidity, and air velocity. The intensity of thermal radiation was measured using a thermal meter "IK-metr". The noise level and general vibration were measured using a GM1351 digital sound level meter and an AR63A (GM63A) vibrometer. Permissible norms of harmful factors were determined in accordance with applicable regulatory documents.

Dependences (1), (2) were used to determine the assessments of indicators of harmful factors Sq on a dimensionless scale. To determine the shape parameter, according to the hierarchy analysis method, the following criteria were considered for paired comparisons: air temperature; relative humidity; air velocity; the intensity of thermal radiation; noise; and local vibration.

The selection of criteria and paired comparisons involved three experts, whose quality of work was verified using the consistency index. When comparing the consistency index with the average consistency, the consistency ratio for the 6th order matrix was 6%, which corresponded to the condition ≤ 10%.

The obtained experimental values of the above indicators of harmful factors and the results of mathematical transformations using the dependence are shown in Table 1.

The measurements were taken over a period of 31 days; therefore, Fig. 3 presents an example of a chart depicting the change in humidity depending on time.

Aiming to adjust the scales for each indicator of a harmful production factor, it is necessary to divide the difference between the minimum and maximum values by the number of intervals (ten such intervals in total), which is on the corresponding intermediate scale.

The graphic model for assessing indicators of harmful factors has the form presented in Fig. 4.

Since assessments of individual indicators of harmful factors have the same measurement scale (0 – 1), the overall index can be found by applying one of the average values. In this case, the geometric mean value is applied.

$$Q = \sqrt[n]{\prod_{i=1}^{n} S_{qi}} = \sqrt[6]{0.96 \cdot 0.91 \cdot 0.62 \cdot 0.3 \cdot 0.5 \cdot 0.65} = 0.61 \quad (6)$$

So, with the help of addition and experts, it is possible to find an overall index of the safety of working conditions in the workplace to determine the shape parameter. Thus, the application of the developed system of relationships between individual indicators of harmful production factors and their values on a dimensionless scale provides a quantitative assessment of the safety of working conditions in the workplace.

Based on the analysis of modern scientific research regarding the assessment of the safety of working conditions, the developed methodology establishes the basic principles and procedure for assessing safety and health at work using the developed system for dependencies of indicators of harmful factors with a dimensionless rating scale. The technique can be applied to all enterprises and organisations to assess harmful and dangerous factors in industrial premises.

Tab. 1. Results of the implementation of the methodology for assessing the safety of working conditions

No.	Indicators of harmful factors	q_{min}	q_{max}	q_{opt}	q_i	r	S_q
1	air temperature, °C	13	19	16	17	0.1	0.96
2	relative humidity, %	25	75	50	70	0.9	0.91
3	air velocity, m/s	0	0.5	0	0.1	0.3	0.62
4	intensity of thermal radiation, W/m²	0	140	0	94	3	0.3
5	noise, dBA	60	80	0	65	0.5	0.5
6	local vibration, m/s²	0	0.2	0	0.09	0.7	0.65

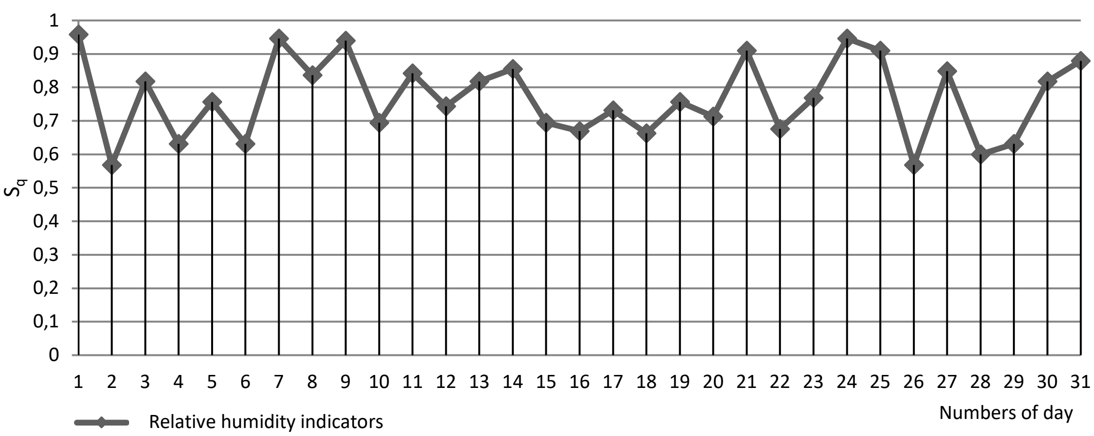

Fig. 3. Chart depicting the passage of time and the change in humidity indicators for 31 days

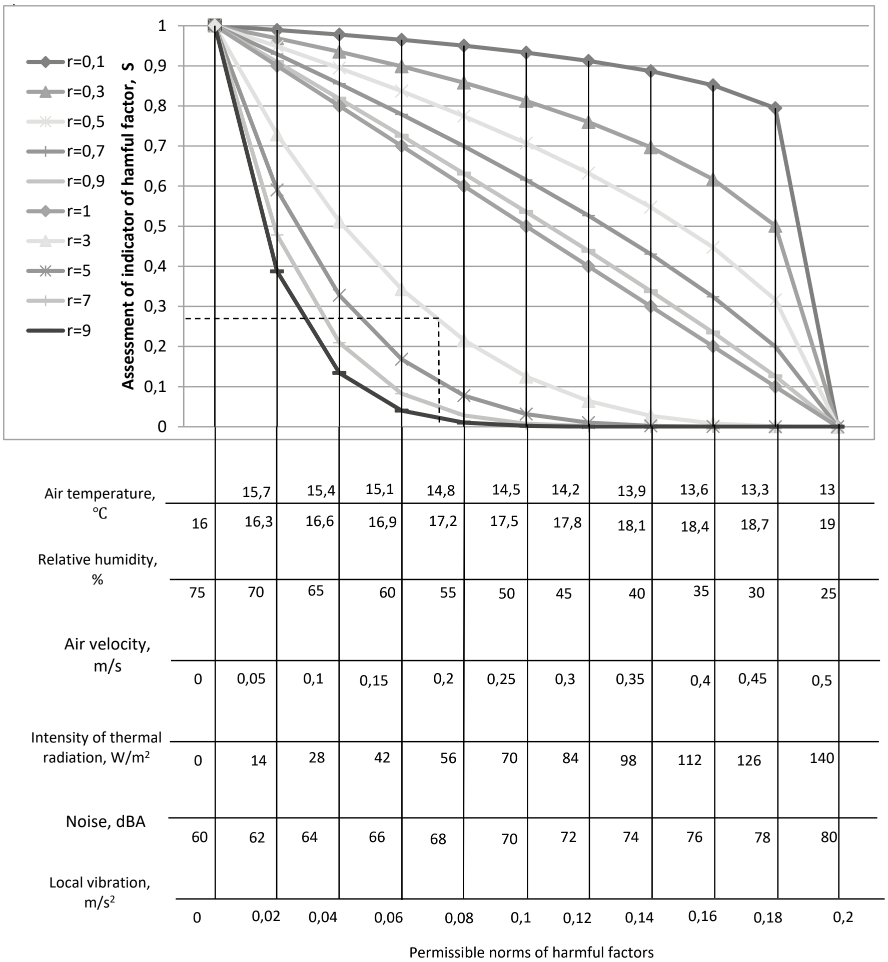

Fig. 4. Graphical model for assessing indicators of harmful factors

Conclusions

The article described the application of a system comprised of ten mathematical dependencies between single different-sized indicators of harmful factors and their assessments on a dimensionless scale from 0 to 1, which made it possible to obtain a quantitative dimensionless assessment of the safety of working conditions in the workplace. A hierarchy analysis method was used to establish the shape parameter of mathematical dependencies based on a paired comparison of factors, to make a decision on determining safety and occupational health assessments from one of ten dependencies. The developed technique was tested at an enterprise. The results confirmed that this technique could be used for a quantitative assessment of the safety of working conditions in the workplace. The obtained results serve as grounds for improving the system of occupational safety management in the workplace.

Further research should consider the assessment of indicators of harmful factors over time and the determination of their numerical characteristics (variance, correlation), as well as examination of other possible dependencies that may result in a more reliable assessment.

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