ISSN 2543-6597

Bialystok University of Technology
Faculty of Engineering Management

sciendo

ISMSME
International Society for Manufacturing, Service and Management Engineering

Engineering Management in Production and Services

Volume 13 • Issue 3 • 2021

Frequency

ECONOMICS AND MANAGEMENT
is published quarterly since 1998

As of the beginning of 2017 the journal
is published under a new name:
ENGINEERING MANAGEMENT
IN PRODUCTION AND SERVICES

Copyrights ©

Publisher

Bialystok University of Technology
Wiejska 45A, 15-351 Bialystok, Poland

The International Society
for Manufacturing Service
and Management Engeneering (ISMSME)

Submission

Papers for submission should be prepared according to the *Authors Instructions* available at www.empas.pb.edu.pl

All papers should be submitted through the electronic submission system

Editor-in-Chief

Joanna Ejdys
Bialystok University of Technology
Faculty of Engineering Management
Wiejska 45A, 15-351 Bialystok, Poland
Phone: (+4885) 746 9802
Fax: (+4885) 663 1988
e-mail: j.ejdys@pb.edu.pl

Indexation

Journal is indexed in SCOPUS, EBSCO Business Source Ultimate (Complete), Norwegian Register for Scientific Journals, Series and Publishers, Index Copernicus, ERIH PLUS, Google Scholar, Central European Journal of Social Sciences and Humanities, Research Papers in Economics (RePEc), BazTech and BazEkon databases

Deputy Editors-in-Chief

Łukasz Nazarko
e-mail: l.nazarko@pb.edu.pl

Katarzyna Halicka
e-mail: k.halicka@pb.edu.pl

Scientific Secretary

Danuta Szpilko
Bialystok University of Technology
Faculty of Engineering Management
Wiejska 45A, 15-351 Bialystok, Poland
Phone: (+4885) 746 9880
Fax: (+4885) 663 1988
e-mail: d.szpilko@pb.edu.pl

Editorial Office

Bialystok University of Technology
Wiejska 45A, 15-351 Bialystok, Poland
Phone: (+4885) 746 9825
Fax: (+4885) 663 1988
www.empas.pb.edu.pl

Technical Editors

Krzysztof Stepaniuk
e-mail: k.stepaniuk@pb.edu.pl

Tomasz Trochimczuk
e-mail: t.trochimczuk@pb.edu.pl

Table of contents

sciendo

ISMSME International Society for Manufacturing, Service and Management Engineering

received: 15 March 2021
accepted: 20 July 2021

pages: 7-24

Optimisation of structural parameters of the industry by the criterion of product innovation

Svitlana Ishchuk Luybomyr Sozanskyy
Ryszard Pukała

ABSTRACT
The industrial sector of the Polish economy plays an important role in ensuring the socio-economic development of the country. The Polish industry accounts for 24.1 % of the country's employed population and 25.1 % of the GVA. The article aims to model the structural parameters of the Polish industrial sector according to the criterion of increasing product innovation level based on a comprehensive assessment of the Polish industry performance in the regional context. The offered method focuses on estimating the industrial sector at the macro and meso levels using a set of indicators for investment, innovation, labour activity, and profitability. Correlation-regression analysis methods were used to prove hypotheses about the impact of product innovation on employment and wages in the industry. To optimise the structure of the Polish industrial sector, an economic-mathematical model was developed, which was solved using the linear programming method. The target functionality of this model is the level of product innovation, at which the gross average monthly wage of Polish industry workers will double (to the EU average). The simulation results, which was based on data from the Central Statistical Office of Poland, provide an analytical basis for selecting industrial policy benchmarks for Poland.

KEY WORDS
industry, efficiency, product innovation, production, models, structure, optimisation

10.2478/emj-2021-0018

Ryszard Pukała

Bronislaw Markiewicz State Higher School of Technology and Economics, Poland
ORCID 0000-0002-2943-8482

Corresponding author:
e-mail: ryszard.pukala@interia.pl

Svitlana Ishchuk

The National Academy of Sciences of Ukraine, Ukraine
ORCID 0000-0002-3698-9039

Lyubomyr Sozanskyy

The National Academy of Sciences of Ukraine, Ukraine
ORCID 0000-0001-7854-3310

Introduction

Industry is an important sector of the European Union's (EU) economy. In Poland, it accounts for 24.1 % of the employed population and 25.1 % of the gross value added (GVA). The industry also plays a key role in ensuring the competitiveness of EU countries, as it accounts for about 60 % of merchandise exports (on average in the EU-28).

Today, according to the European Classification of Economic Activities NACE Rev.2, the industry

Ishchuk, S., Sozanskyy, L., & Pukała, R. (2021). Optimisation of structural parameters of the industry by the criterion of product innovation. *Engineering Management in Production and Services, 13*(3), 7-24. doi: 10.2478/emj-2021-0018

includes the following types of industrial activity: mining and quarrying; processing industry manufacturing (which consisting of 36 productions); electricity, gas, steam and air conditioning supply, water supply; sewerage, waste management and remediation activities. The industry operation is influenced by a large number of different dynamic (or rapidly changing) factors. It is, e.g., world market conditions, access to foreign commodity and raw materials markets, global competition and concentration of products, and force majeure. One of the most important dynamic factors hindering the development of the industrial sector of the economy in 2020 was quarantine restrictions imposed by governments to curb the spread of the COVID-19 pandemic. In the first half of 2020, compared to the same period of 2019, Poland saw a decrease in the volume of industrial production to 6.8 percentage points (pp). The decline in industrial production occurred in 15 of the 16 regions of the country.

1. Literature review

In addition to dynamic factors, the results of industrial functioning are significantly (and in some cases decisively) influenced by relatively stable factors, including the scale of production, adequacy and efficiency of capital investment, innovation of industrial products, and labour productivity. These categories are both factors and results of the industrial sector functioning. The results of each category analysis and comprehensive assessment generally form the basis for diagnosing problems and prospects of the industry. Such a basis can be used to develop managerial tactical and strategic decisions to regulate the macro and meso levels of the industrial sector towards targeted restructuring. This article is a logical continuation and further expansion of the author's research results aiming to update issues of the industrial sector competitiveness, substantiate ways to increase socio-economic efficiency of the industry in EU countries and optimise the structure of the manufacturing industry. Ishchuk (2018) and Sozansky (2018 a, 2018 b, 2017) developed and tested an original methodology for assessing the industry's competitive advantages in Ukrainian regions, based on a comprehensive system of indicators characterising key aspects, results and factors of the industry. The main applied results of this methodology were: rating and grouping of regions of Ukraine by values of integrated activity indicators (production, capital, investment, innovation, and export) and industry efficiency (economic and resource), identifying competitive advantages and weaknesses of the industrial sector of the economy in 24 Ukrainian regions.

Another critical research result was to identify the transformational trend of the industrial sector of Ukraine's economy in the regional context. The essence of this trend is the formation of new industrial centres that are still small but have higher (compared to the old industrial regions) economic efficiency indicators for industrial enterprises, labour productivity, the level of manufacturability and innovation. Such new industrial centres are primarily located in regions with high unemployment and low wages. The industry priorities in these regions are manufacturing products with a relatively higher share of GVA and the degree of processing of raw materials, reducing the resource intensity of products and their high export orientation, particularly to EU markets. In addition, the method was used to make a comparative assessment of the competitive advantages of Ukrainian and Polish industries at the macro level and the Lviv region and Subcarpathia Voivodeship at the meso level.

Therefore, it became relevant to consider the developed methodology's universality for assessing the industrial sector's functioning in other countries, including the EU. One of the reasons was the variety of approaches used by the industry to choose indicators and algorithms for their analysis. Pla-Barber and Villar (2019) conducted a quantitative assessment of companies of the Spanish automotive and textile industries in the context of GVA chains and determined the shares of sales, GVA, average wages per employee and employment.

An assessment of structural changes in the Czech economy in 1996–2002 using the DSGE (dynamic stochastic general equilibrium) model, estimated with Bayesian methods, is given by Čapek (2016). Wlodarczyk (2013) provided an overview of structural changes in the Polish food industry in 2000–2012 and used nonlinear programming methods to optimise the structure of production factors. Kudełko (2016) assessed the industry's role in the economy of Polish regions and calculated indicators of the industry's share in sales, employment, and region's GVA. At the same time, the study of the industrial sector of the Polish economy ignored the issue of its comprehensive assessment in the regional context. Few publications on this topic considered some, the most important aspects of economic activity or key industry sectors. Also, these and the other studies paid

insufficient attention to modelling the impact of structural parameters of the processing industry on its efficiency (economic and social). In addition, research on this topic rarely uses a comprehensive scientific approach, which covers the whole spectrum from problem argumentation, proposing and confirming hypotheses, to justification and testing through modelling.

An essential component and indicator of industrial development is the innovation of its products. Kongaut and Bohlin (2017) found that broadband speeds had a positive effect on the gross domestic product, and this effect was higher in lower-income countries. According to Dąbrowski (2018), market information received from consumers and businesses (excluding competitors) has a positive effect on product innovation. Kotowicz-Jawor (2019) analysed the relationship between the current developmental stage of the Polish economy and the determinants of its innovation potential in the context of the EU structural funds. An important result of this study was the assertion that the economic growth of the Polish economy depended more on external funding sources (EU funds, foreign investment) than on the domestic innovation potential. Pidorycheva and Kovchuha (2019) determined that the total amount of innovation costs was somewhat closely related to the volume of sold innovative products.

To assess the industry's innovativeness in Lower Silesia Voivodeship, Brezdeń and Spallek (2013) calculated the following indicators of innovation: innovation activity, expenditures on innovations, income, type of products (new or improved), and production equipment. These indicators were integrated into the synthetic indicator. The innovativeness of Polish voivodships was calculated using a synthetic indicator consisting of indicators derived by Janiszewska and Ossowska (2017). The synthetic indicator was used as the basis to determine the regions with the highest and the lowest levels of innovation. The assessment of the road transport development in Polish voivodships and its impact on the socio-economic indicators of the region was carried out using a taxonomic indicator and econometric analysis as highlighted by Czech and Lewczuk (2016).

The reviewed research highlighting the innovation of the Polish industry showed insufficient attention paid to the following aspects.

Product innovation in combination with other interrelated indicators that reflect the economic conditions for innovation and the consequences (impact) of innovation on the economic performance of enterprises in Poland and its regions were studied by Lubacha (2019), Golejewska (2018), Zakrzewska and Chojnacki (2020), Chybowska, Chybowski and Souchkov (2018), and Węglarz (2018). Product innovation research without a parallel assessment of other direct links of economic activity in industrial enterprises fails to reflect the impact of economic preconditions on innovation and socio-economic situation and performance results of enterprises in the region.

Many studies into a comprehensive economic activity assessment of the economy's real sector in Polish regions, such as by Adamowicz (2021), Miłek and Mistachowicz (2019), Tereszczuk (2015), and Gajda (2016), consider the current state of investigated processes for the last year or three, but usually disregard transformation processes, dynamic changes occurring over certain cycles, and larger time measurement ranges. Failure to consider such more global changes makes it is impossible to weigh prospects and make an objective assessment of global and transformational processes, which are important when considering the economic activity in the regions.

The studies assessing the economic processes of Polish regions use integrated taxonomic and consolidated indicators for the study period. Majka and Jankowska (2017), Godinho, Mendonça and Pereira (2005), and Lubacha (2019) mainly analysed the current state for the selected years. Dynamic indicators, and especially those with a reasonably long period of cyclical, structural or transformational changes, are not considered or included as components of integrated indicators.

Some studies, such as by Bierut (2016, pp. 79-82), Piłka (2019, p. 28), Karpińska (2018, p. 227), Karpińska and Protasiewicz (2019), assume or theorise about the relationship between innovation and workers' wages, innovation and employment. However, no available and reviewed resources were found to provide the numerical expression of the closeness of such relationships, their directions, statistical characteristics on the example of the Polish industry or other economic sectors. The substantiation and quantitative and qualitative characteristics of such relationships are the basis for forecasting, research, modelling and stimulation of many socio-economic and financial processes. Information about the relationship between innovation and wages and possible investment in innovation can help determine the dynamics of migration processes and, thus, the key socio-economic indicators used to calculate tax revenues and expenditures of regional and central budgets and business activity indicators of the studied sectors.

The topic of structural parameter optimisation in the Polish industry was not reflected in the reviewed scientific research. At the same time, one of the most relevant aspects of the macroeconomic regulation and stimulation of the country's industrial development is the identification of industrial production that can give the greatest multiplier effect on the national socio-economic development due to higher product innovation. Therefore, such information can contribute to more rational use and attraction of investment resources or financial support. As innovation in modern conditions is the most important driver for the national socio-economic development, it justifies the need to optimise the volume of sold industrial products (as one of the key structural parameters) by the criterion of innovation. Therefore, the following economic model construction is substantiated as it will show the structure of sold industrial products required to achieve the desired level of innovation and other social indicators, such as the desired average wage, employment and macroeconomic components (dynamics of labour migration, income and expenditure to budgets, etc.).

Therefore, this study was relevant and also directed to address the identified theoretical and methodological and practical gaps in addition to practical aspects.

The article aims to model the structural parameters of the industrial sector of the Polish economy by the criterion of increased product innovation level based on a comprehensive assessment of the Polish industry operation in the regional context.

2. Methodology

The article presents an original method of a comprehensive assessment of trends and results of the industrial sector of the economy at the macro and meso levels. It is formed according to the principles and approaches of the methodology tested on the example of Ukraine (Ishchuk, 2018), but at the same time, it is improved and expanded to fit the purpose of this study, based on indicators that can be calculated from open statistics.

The algorithm for implementing the developed methodology includes three main stages.

The first stage involves calculating the level of industrialisation and innovation of the country's economy in terms of its regions. The method proposes to determine the economy's level of industrialisation and innovation at the meso level by indicators of the industry's share in each of the regions in key absolute indicators of the industrial sector. These indicators include the volume of sold industrial products, the GVA industry, the cost of innovative activities of industrial enterprises, and the net income from the sale of innovative products. The relevant regional structures are built based on calculated results of the region's share in these indicators for the selected period (ten years). Such structures clearly demonstrate the current level and dynamics of industrialisation and innovation of the regional economy.

The second stage involves an integrated assessment of the industrial sector's efficiency at the macro and meso levels. The algorithm for implementing this step is schematically presented in Table 1.

A detailed applied analytical research and expert-logical approach resulted in investment, labour and innovation activity, and profitability determined as the most important indicators of industrial functioning from the standpoint of economic and social efficiency and development prospects. These indicators are both results and factors in the industry functioning as they are closely interrelated.

Twelve indicators were selected for the analysis to comprehensively reflect the results of the industrial sector's functioning at the macro and meso levels. Each of these indicators is a stimulant, i.e., the higher the value of the indicator, the higher the result of the activity it characterises. The selected indicators can be calculated from open statistics.

In addition, the authors propose to assess the effectiveness of the industrial sector both by current values of the selected indicators and by indices of the dynamics of these indicators (for a period of ten years). This will allow to compare the current (actual) and previous levels of the industry's efficiency in the country and its regions and to diagnose the change trend in this level.

Hellwig method was used to bring the multidimensional values of the selected indicators-stimulators into a comparable form (Hellwig, 1968):

The application of formula (1) allows placing all the actual values of the indicators listed in Table 1

$$Y = \frac{Z_{ij} - Z_{min}}{Zmin_{max}} \quad (1)$$

where:

Y – the normalised indicator-stimulator;

Z_{ij} – the actual value of the i-th indicator in the j-th region

Z_{min} – the minimum value of the i-th indicator in the sample (study regions)

Z_{max} – the maximum value of the i-th indicator in the sample

Tab. 1. Efficiency indicators of the industrial sector

PERFORMANCE INDICATORS	THE INDICATORS OF THE CURRENT STATE	THE INDICATORS OF DYNAMICS (FOR A PERIOD OF 10 YEARS)
Investment activity	The investment outlays per one employee (x_1^{kf})	The index of investment expenditures per employee (x_1^{kd})
	The value of investment outlays per one employee (x_2^{kf})	The index of the value of investment outlays per employee (x_2^{kd})
	The expenditures on innovation activity per one employee (x_3^{kf})	The index of expenditures on innovation activity per employee (x_3^{kd})
	The taxonomic indicator of current investment activity $X^{kf} = (x_1^{kf} + x_2^{kf} + x_3^{kf})/3$	The taxonomic indicator of the dynamics of investment activity $X^{kd} = (x_1^{kd} + x_2^{kd} + x_3^{kd})/3$
The general taxonomic indicator of investment activity $X^k = (X^{kf} + X^{kd})/2$		
Labour activity	The GVA per employee in the industry (x_1^{lf})	The index of GVA per employee in the industry (x_1^{ld})
	The sold production of industry per employee (x_2^{lf})	The index of sold production of industry per employee (x_2^{td})
	The gross monthly average salary of the employed (x_3^{lf})	The index of the gross monthly average salary of the employed (x_3^{ld})
	The taxonomic indicator of the current labour activity $X^{lf} = (x_1^{lf} + x_2^{lf} + x_3^{lf})/3$	The taxonomic indicator of the dynamics of labour activity $X^{ld} = (x_1^{ld} + x_2^{ld} + x_3^{ld})/3$
	The general taxonomic indicator of labour activity $X^L = (X^{lf} + X^{ld})/2$	
Innovative activity	The share of net revenues from the sale of innovative products in the net revenues from the sale of industrial enterprises in general (x_1^{if})	The index of the share of net revenues from the sale of innovative products in the net revenues from the sale of industrial enterprises in general (x_1^{id})
	The share of net revenues from the sale of innovative products for the market in the net revenues from the sale of industrial enterprises in general (x_2^{if})	The index of the share of net revenues from the sale of innovative products for the market in the net revenues from the sale of industrial enterprises in general (x_2^{id})
	The share of net revenues from the sale of innovative products for the market for a market on export in the net revenues from the sale of industrial enterprises in general (x_3^{if})	The index of the share of net revenues from the sale of innovative products for the market for a market on export in the net revenues from the sale of industrial enterprises in general (x_3^{id})
	The taxonomic indicator of current innovation activity $X^{if} = (x_1^{if} + x_2^{if} + x_3^{if})/3$	The taxonomic indicator of the dynamics of innovation activity $X^{id} = (x_1^{id} + x_2^{id} + x_3^{id})/3$
	The general taxonomic indicator of innovation activity $X^I = (X^{if} + X^{id})/2$	
Profitability of activity	The profitability on assets (x_1^{pf})	The index of the profitability on assets (x_1^{pd})
	*The profitability of products of the employed (x_2^{pf})	*The index of the profitability of products of the employed (x_2^{pd})
	The profitability on turnover (x_3^{pf})	The index of profitability on turnover (x_3^{pd})
	The taxonomic indicator of current economic efficiency $X^{pf} = (x_1^{pf} + x_2^{pf} + x_3^{pf})/3$	The taxonomic indicator of the dynamics of economic efficiency $X^{pd} = (x_1^{pd} + x_2^{pd} + x_3^{pd})/3$
	The general taxonomic indicator of profitability $X^P = (X^{pf} + X^{pd})/2$	
The integral indicator of the current state $I^f = \sqrt[4]{X^{kf} X^{lf} X^{if} X^{pf}}$		The integral indicator of dynamics $I^d = \sqrt[4]{X^{kd} X^{ld} X^{id} X^{pd}}$
The final integrated indicator of the industry's efficiency $I = \sqrt[4]{X^K X^L X^I X^P}$		

*The profitability of products of the employed — the indicator, calculated as the ratio of the net financial result per employee in the industry to the average annual salary of the employed in the industry

into the range from 0 to 1. The regions with the highest value of each indicator will correspond to the maximum level of 1, and with the minimum of 0. Thus, all regions for each indicator will be placed in the order of distance from the region with the maximum value of the indicator.

For each of the four selected performance indicators (investment, labour, innovation and profitability), the calculation of taxonomic indicators of the current state and dynamics, which are defined as the arithmetic mean of the three standardised indicators for each indicator. General taxonomic indicators are calculated as the arithmetic mean of taxonomic indicators of the current state and dynamics. The integrated indicator of the current state is defined as the geometric mean of four taxonomic indicators of the current state (for each of the four efficiency indicators).

The third stage of the study involves ranking the regions by values of integrated indicators of the current state and dynamics and the final integrated indicator of the efficiency of the industrial sector of the economy using the method of k-average.

3. Results

The developed methodology was implemented on the example of an industry in Polish regions. In particular, the results of the calculation of the industrialisation of the economy showed that industrial production in Poland was mainly concentrated in traditional industrial regions. In 2019, four voivodships, namely, Lower Silesia, Mazovia, Silesia and Greater Poland, were responsible for 56.6 % of sold industrial products (Table 2). In 2018, these voivodships also accounted for 52.8 % of the industry's GVA.

Mazovia, Silesia and Greater Poland also dominate in terms of innovation: in 2018, they accounted for a total of 56.5 % of net income from the sale of innovative products. At the same time, expenditures on innovative activities of industrial enterprises in these voivodships amounted to 40.4 % of the total in Poland. Also, during 2009–2018, the costs of innovative activities of industrial enterprises increased significantly in Lódz, Lesser Poland and Subcarpathia.

The implementation results of the second stage of the methodology (efficiency assessment of the industrial sector of Poland and its regions) revealed a relatively high level of current innovation activity in Lesser Poland and Subcarpathia, as well as the significant dynamics in the share of the net income from sales of innovative products in the net income from sales of industrial enterprises in general in Lódz (Table 3).

In Lódz, Lesser Poland and Subcarpathia, the indices of labour productivity (the volume of indus-

Tab. 2. Regional structure of the Polish industry and innovation, %

Indicator / Region	Level of industrialisation						Innovation					
	Realised industrial products			Industry's GVA			Expenditures on innovative activities of industrial enterprises			Net income from the sales of innovative products		
	2009	2019	increase	2007	2017	increase	2008	2018	increase	2008	2018	increase
Poland	100.0	100.0	x	100.0	100.0	x	100	100	x	100.0	100.0	x
Lower Silesia	9.1	8.8	-0.3	11.0	10.3	-0.7	7.3	5.2	-2.1	5.7	5.2	-0.5
Kuyavia-Pomerania	4.4	4.2	-0.2	4.8	4.7	-0.2	7.4	2.6	-4.8	4.4	2.5	-1.9
Lublin	2.3	2.6	0.3	3.1	3.1	0.0	3.3	3.2	-0.2	1.6	1.0	-0.7
Lubusz	2.5	2.5	0.1	2.8	2.8	0.0	1.4	1.9	0.4	2.1	3.0	0.9
Lódz	5.3	5.5	0.2	6.8	6.8	0.1	9.7	15.0	5.3	2.8	4.1	1.3
Lesser Poland	5.8	7.2	1.4	7.2	6.9	-0.3	5.2	10.0	4.8	7.0	8.6	1.6
Mazovia	20.6	20.1	-0.5	13.6	15.1	1.5	20.7	16.8	-3.9	26.4	28.6	2.2
Opole	2.3	2.2	-0.1	2.7	2.4	-0.3	1.2	2.3	1.1	1.4	1.6	0.2
Subcarpathia	3.0	3.5	0.5	4.1	4.6	0.4	4.0	8.2	4.3	3.1	2.8	-0.4
Podlaskia	1.8	2.0	0.2	1.9	1.9	0.0	1.8	1.0	-0.8	1.3	1.1	-0.1
Pomerania	5.9	6.4	0.5	5.7	5.9	0.2	9.2	5.3	-3.9	15.3	7.4	-7.9
Silesia	18.7	15.7	-3.0	17.4	16.4	-1.0	17.5	14.1	-3.3	15.8	15.3	-0.5
Swietokrzyskie	2.2	2.0	-0.1	2.8	2.3	-0.5	1.8	1.3	-0.5	1.7	0.8	-0.9
Warmia-Masuria	2.3	2.4	0.1	2.7	2.7	0.0	1.3	1.3	0.1	2.0	2.1	0.1
Greater Poland	11.0	12.0	1.0	10.3	11.0	0.7	6.5	9.5	2.9	6.9	12.6	5.7
West Pomerania	2.8	2.8	0.0	3.1	3.2	0.1	1.6	2.3	0.7	1.4	0.8	-0.6

Source: elaborated by the authors based on CSOP (2020).

trial output per employee) and gross average monthly wages exceeded the average values of these indicators in Poland. However, the gross monthly average wage of workers in these voivodships was lower than the average in Poland. The highest values of this indicator were maintained in traditionally industrial regions, i.e., Lower Silesia, Mazovia and Silesia. These three voivodships were also characterised by a high level of return on assets, and, in particular for Mazovia and Lower Silesia, the high level of profitability in general. In terms of dynamics, the industry also showed the highest profitability in Lesser Poland and Subcarpathia (Table 4).

Mazovia is the leader in the ranking of Polish regions in terms of the values of the overall integrated indicator of industrial functioning despite the decline in investment activity of its industry (Table 5). The industrial structure of this voivodeship is dominated by food production (19.9 %) and the production and supply of electricity, gas, steam and hot water (17.2 %). The share of innovative products in sales of the food industry was 18.3 % and 0.9 % in the production and supply of electricity, gas, steam and hot water. At the same time, in the structure of the industry, Mazovia had small shares of production with a significantly higher level of product innovation. The production of electrical equipment and paper and printing products (with the share of innovative products in sales amounting to 35.2 % and 32.7 %, respectively) occupied only 5.2 % and 1.2 % in the structure of sold industrial products of the voivodship. Thus, the industrial sector of the economy of Mazovia, which produces more than 20 % of Poland's industrial output, is the leader in the value of the overall integrated indicator and the integrated indicator of the current state by a wide margin but not the dynamics.

Instead, the highest dynamics of industrial functioning indicators is demonstrated by Subcarpathia, which occupies the third position in the ranking by the values of the general integrated indicator. It should be noted that the innovative activity of the industrial sector of this voivodship (both in terms of the current status and dynamics) significantly exceeded the average level of Poland. This is due to the high values of the share of innovative products that are new to the market and new to the export market. In addition, the index of innovation spending per employee was the highest in Poland.

The industry structure of Subcarpathia is highly diversified. It has four sectors (production of rubber and plastic products; production of metal products; production of cars, trailers and semi-trailers; production of other transport equipment) occupying 10–12 % each, and three (food production, production of products from wood, cork, straw, production of machines and devices) with more than 7 % each. At the same time, the level of innovation of these industries is in the range of 15 to 21 %.

Subcarpathia (as opposed to Mazovia) does not belong to traditional industrial regions as its share in the volume of sold industrial products of the Polish industry only amounts to 3.5 %, and the values of current indicators of labour productivity and capital investment are very low. However, over the past ten years, the industry of this region has significantly increased the level of product innovation, the profitability of turnover and assets, and the cost of innovation per employee. This gives grounds to suggest that should Subcarpathia continue with such positive trends, it has the prospect of becoming one of the new Polish innovation and industry centres.

In general, all regions of Poland can be divided into three groups by type of industry:

- the first group contains traditionally industrial voivodships with a high level of the industrial economy but also exhibiting signs of reduced potential, the need to diversify and optimise the structure of the industry, primarily based on increasing product innovation (Mazovia, Lower Silesia, Silesia, Greater Poland, Lesser Poland, Lódz, Pomerania);
- the second group accommodates voivodships with a low share in the national industry and characterised by medium or low values of partial indicators for the current state of labour activity, but high values of indicators for innovation activity and having the most indicators of dynamics (Subcarpathia, Podlaskia, Opole, Lublin, Lubusz); and
- the third group includes voivodships characterised by a non-industrial type of economy and mostly low values of industrial activity (Warmia-Masuria, Swietokrzyskie, West Pomerania, Kuyavia-Pomerania).

Despite growing investments in the industrial sector of the Polish economy, the decline is observed in labour, innovation and profitability of Polish industrial enterprises. This is confirmed by lower values of dynamics indicators compared to indicators of the current state and too innovative activity (0.36 vs 0.53). Therefore, the conducted analytical studies led to a conclusion that the greatest issue of the Polish industry is low innovation activity, which is among the lowest in the EU.

Tab. 3. Actual values of industrial functioning indicators of Poland and its regions*

Region	Investment activity						Labour activity						Innovation activity						The profitability of activity					
	Capital investment per employee, thousand PLN	Capital investment index per employee	Cost of capital investment per employee, thousand PLN	Capital investment value index per employee	Expenditure on innovation activities per employee, thousand PLN	Index of costs for innovation activities per employee	GVA labour per employee in the industry	GVA index per employee in the industry	Volume of sold industrial products per employee, thousand PLN	Index of sales of industrial products per employee	Gross monthly average salary of an employee, thousand PLN	Index of the gross monthly average wage of an employee	Share of the net income from sales of innovative products in net income from sales of industrial	Index of the share of net income from sales of innovative products in net income from sales of industrial	Share of net income from sales of innovative products for the market in net income from sales of industrial	Index of the share of net income from sales of products innovative for the market in net income from sales of	Share of net income from sales of products innovative for the export market in net income from sales of	Index of the share of net income from the sale of innovative products for the export market in the net	Return on assets, %	Return on assets index	Profitability of wages per employee, %	Index of profitability of wages per employee	Profitability of turnover (net), %	Profitability index of turnover
Poland	**28.57**	**1.31**	**104.2**	**1.39**	**8.0**	**0.94**	**151.1**	**1.74**	**523.44**	**1.65**	**4.68**	**1.58**	**9.1**	**0.73**	**3.2**	**0.49**	**1.7**	**0.63**	**4.9**	**1.48**	**33.14**	**1.43**	**4.7**	**1.42**
Lower Silesia	34.17	1.55	122.0	1.65	5.2	0.71	180.5	1.56	547.38	1.73	5.26	1.63	7.2	0.68	3.2	0.45	1.7	0.35	5.7	2.92	25.48	1.78	5.2	2.67
Kuyavia-Pomerania	16.18	0.82	82.9	1.23	4.2	0.34	129.2	1.70	438.79	1.61	4.03	1.59	6.3	0.42	2.3	0.50	0.5	0.47	7.8	3.35	32.54	1.62	6.0	2.59
Lublin	35.99	2.06	106.3	1.33	6.9	0.80	131.2	1.78	369.97	1.50	4.32	1.63	4.9	0.79	2.1	0.52	0.8	0.98	4.7	0.78	38.58	1.04	5.5	0.91
Lubusz	18.67	1.23	82.2	1.42	5.7	1.21	147.1	1.71	493.86	1.98	4.32	1.72	12.8	0.83	1.6	0.18	0.7	0.47	6.2	2.32	24.12	1.52	4.1	1.53
Lódz	43.66	1.69	87.0	1.21	18.4	1.58	142.1	1.88	452.40	1.93	4.41	1.75	9.2	1.15	1.8	0.55	0.5	0.48	3.8	0.87	27.25	1.22	4.1	0.94
Lesser Poland	30.08	1.51	104.0	1.33	10.8	1.72	137.3	1.59	480.23	1.70	4.43	1.58	12.1	0.87	4.7	0.48	2.3	0.42	6.0	1.32	40.44	1.39	6.1	1.33
Mazovia	39.78	1.30	165.7	1.32	9.6	0.71	206.0	2.04	752.43	1.54	5.20	1.54	10.3	0.77	3.2	0.67	1.9	0.74	5.9	2.88	42.45	2.10	5.5	2.67
Opole	18.31	1.18	113.3	1.97	8.4	1.96	146.2	1.55	491.78	1.47	4.38	1.56	8.0	0.94	5.2	0.90	3.4	1.57	4.8	0.48	29.21	1.15	3.7	0.88
Subcarpathia	22.57	1.45	96.6	1.75	13.6	1.99	126.6	1.86	355.35	1.69	4.08	1.63	9.0	0.67	4.7	0.88	2.4	0.80	5.1	3.33	27.25	1.27	4.2	2.76
Podlaskia	25.90	1.35	133.5	1.60	4.1	0.53	132.2	1.68	491.68	1.82	4.07	1.59	6.5	0.76	2.9	0.54	1.3	2.36	4.8	3.82	24.36	1.37	3.4	2.73

Pomerania	22.00	0.94	118.4	1.43	7.5	0.56	150.7	1.77	604.47	1.71	4.63	1.54	9.8	0.35	4.8	0.19	3.1	0.53	7.1	3.24	48.25	1.37	5.3	2.40
Silesia	28.75	1.27	72.6	1.30	7.1	0.80	156.9	1.70	531.73	1.52	5.28	1.47	8.8	0.76	3.0	0.58	1.8	0.79	5.7	1.98	27.46	0.86	2.7	0.93
Swietokrzyskie	15.29	0.47	79.2	1.08	4.2	0.71	131.8	1.55	432.21	1.44	4.10	1.53	4.5	0.49	2.7	0.55	0.9	0.75	5.3	0.58	45.21	0.85	4.3	0.47
Warmia-Masuria	17.70	1.50	102.0	1.55	3.3	0.96	119.3	1.72	390.13	1.74	3.88	1.63	8.9	0.67	1.9	0.58	0.9	0.77	5.2	3.93	27.36	1.14	3.7	2.80
Greater Poland	23.20	1.33	77.9	1.31	6.2	1.29	137.8	1.75	504.97	1.77	4.49	1.64	10.0	1.20	3.2	0.73	1.1	0.56	5.8	1.58	33.62	1.34	4.5	1.24
West Pomerania	20.67	1.20	114.6	1.31	5.3	1.38	131.9	1.80	429.27	1.60	4.32	1.62	3.2	0.37	0.9	0.28	0.4	0.22	4.9	4.44	26.78	1.12	4.1	3.73

*All indices were calculated as the ratio of 2018 to 2008.

Source: elaborated by the authors based on CSOP (2020).

Again, the analytical research has led to the conclusion that the big issue of the Polish industry is low innovation activity, which is among the lowest in the EU. Thus, the Polish industry, in terms of the share of the net income from the sale of innovative products in the net income from the sale of industrial enterprises in general, is significantly inferior to the German (Fig. 1).

At the same time, there is an average correlation between the values of this indicator in these countries (the correlation coefficient of 0.63). This can be explained by the integration of individual links in the global value chain as well as the action of the same factors influencing the development of the industrial sector of the economy of Poland and Germany.

This study focused on innovation activity because, under modern conditions for industrialised countries, industrial innovation is one of the decisive factors in ensuring the economic and social efficiency of the economy. Thus, studies (ZEW, 2020) have shown that product innovation significantly affects the performance of the industry. In particular, the surveyed German industrialists believed that improving product quality by increasing its innovation to 2.4 % increased sales and reduces production costs to 3.7 %.

On the other hand, a systematic review of research on innovation presented by Bierut (2016, pp. 79–82) suggested that increasing innovation increased labour market rotation. In some small and medium-sized firms, it could have led to lower employment through the release of "old" products, while in new and large firms, it could have become a factor in new job creation. As noted, "innovation is a source of rising wage inequality"; therefore, workers with the highest level of qualifications may see a rise in wages, and those with the lowest qualifications (doing routine work) may experience a decrease in the remuneration. The issue related to the impact made by product innovation on wages and employment in the industry is especially relevant in the era of the spread of Industry 4.0 and the growth of labour migration in Europe. Thus, there is a pressing need to determine the impact of innovation on key socio-economic indicators of the Polish industry, especially considering the fears that the growth of industrial product innovation will cause two very serious social problems: lower wages and lower employment in the industry. This study puts forward two scientific hypotheses.

The first hypothesis states that the growth of innovation activity contributes to increased employ-

Tab. 4. Taxonomic indicators of the industry's functioning in Poland and its regions

REGION	INVESTMENT ACTIVITY			LABOUR ACTIVITY			INNOVATION ACTIVITY			PROFITABILITY OF ACTIVITY			INTEGRAL INDICATOR		
	INDICATOR OF THE CURRENT STATE	INDICATOR OF DYNAMICS	OVERALL FIGURE	INDICATOR OF THE CURRENT STATE	INDICATOR OF DYNAMICS	OVERALL FIGURE	INDICATOR OF THE CURRENT STATE	INDICATOR OF DYNAMICS	OVERALL FIGURE	INDICATOR OF THE CURRENT STATE	INDICATOR OF DYNAMICS	OVERALL FIGURE	INDICATOR OF THE CURRENT STATE	INDICATOR OF DYNAMICS	OVERALL FIGURE
Poland	**0.37**	**0.41**	**0.39**	**0.45**	**0.39**	**0.42**	**0.53**	**0.36**	**0.44**	**0.42**	**0.34**	**0.38**	**0.44**	**0.37**	**0.41**
Lower Silesia	0.44	0.51	0.48	0.73	0.37	0.55	0.46	0.28	0.37	0.42	0.68	0.55	0.50	0.44	0.48
Kuyavia-Pomerania	0.07	0.13	0.10	0.14	0.35	0.25	0.23	0.21	0.22	0.77	0.67	0.72	0.20	0.28	0.25
Lublin	0.44	0.52	0.48	0.16	0.38	0.27	0.20	0.45	0.32	0.55	0.12	0.34	0.30	0.32	0.34
Lubusz	0.13	0.46	0.29	0.33	0.74	0.54	0.42	0.22	0.32	0.34	0.44	0.39	0.28	0.43	0.38
Lódz	0.72	0.55	0.64	0.30	0.86	0.58	0.29	0.52	0.41	0.18	0.18	0.18	0.33	0.46	0.41
Lesser Poland	0.45	0.59	0.52	0.31	0.32	0.31	0.81	0.37	0.59	0.75	0.31	0.53	0.54	0.38	0.47
Mazovia	0.76	0.34	0.55	0.98	0.48	0.73	0.59	0.47	0.53	0.70	0.76	0.73	0.75	0.49	0.63
Opole	0.29	0.81	0.55	0.34	0.12	0.23	0.83	0.77	0.80	0.26	0.12	0.19	0.38	0.31	0.37
Subcarpathia	0.40	0.79	0.59	0.08	0.55	0.31	0.72	0.54	0.63	0.30	0.59	0.44	0.28	0.61	0.48
Podlaskia	0.36	0.42	0.39	0.21	0.46	0.33	0.37	0.66	0.52	0.16	0.65	0.40	0.26	0.54	0.41
Pomerania	0.34	0.27	0.30	0.51	0.40	0.45	0.83	0.06	0.44	0.87	0.57	0.72	0.59	0.24	0.46
Silesia	0.24	0.34	0.29	0.63	0.15	0.39	0.51	0.43	0.47	0.21	0.18	0.19	0.36	0.25	0.32
Swietokrzyskie	0.04	0.08	0.06	0.16	0.07	0.12	0.24	0.31	0.27	0.58	0.01	0.29	0.18	0.06	0.15
Warmia-Masuria	0.13	0.52	0.32	0.03	0.49	0.26	0.33	0.39	0.36	0.26	0.61	0.44	0.14	0.49	0.34
Greater Poland	0.18	0.46	0.32	0.34	0.53	0.44	0.49	0.64	0.57	0.47	0.30	0.39	0.34	0.47	0.42
West Pomerania	0.26	0.45	0.35	0.22	0.44	0.33	0.00	0.06	0.03	0.27	0.74	0.50	0.00	0.30	0.20

Source: elaborated by the authors based on CSOP (2020).

Tab. 5. Ranking of Polish regions according to the values of integrated indicators of industrial functioning

№	GENERALISED INDICATOR		PARTIAL INDICATOR OF THE ACTUAL SITUATION		PARTIAL INDICATOR OF DYNAMICS	
1	Mazovia	0.63	Mazovia	0.75	Subcarpathia	0.61
2	Lower Silesia	0.48	Pomerania	0.59	Podlaskia	0.54
3	Subcarpathia	0.48	Lesser Poland	0.54	Warmia-Masuria	0.49
4	Lesser Poland	0.47	Lower Silesia	0.50	Mazovia	0.49
5	Pomerania	0.46	**Poland**	**0.44**	Greater Poland	0.47
6	Greater Poland	0.42	Opole	0.38	Lódz	0.46
7	**Poland**	**0.41**	Silesia	0.36	Lower Silesia	0.44
8	Lódz	0.41	Greater Poland	0.34	Lubusz	0.43
9	Podlaskia	0.41	Lódz	0.33	Lesser Poland	0.38
10	Lubusz	0.38	Lublin	0.30	**Poland**	**0.37**
11	Opole	0.37	Subcarpathia	0.28	Lublin	0.32
12	Lublin	0.34	Lubusz	0.28	Opole	0.31
13	Warmia-Masuria	0.34	Podlaskia	0.26	West Pomerania	0.30
14	Silesia	0.32	Kuyavia-Pomerania	0.20	Kuyavia-Pomerania	0.28
15	Kuyavia-Pomerania	0.25	Swietokrzyskie	0.18	Silesia	0.25
16	West Pomerania	0.20	Warmia-Masuria	0.14	Pomerania	0.24
17	Swietokrzyskie	0.15	West Pomerania	0.00	Swietokrzyskie	0.06

Source: elaborated by the authors based on CSOP (2020).

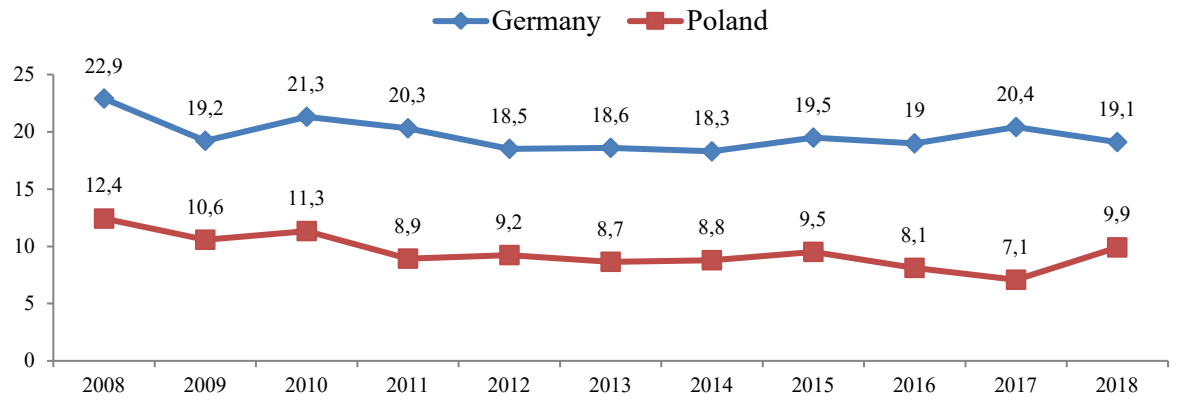

Fig. 1. Share of the net income from sales of innovative products in the net income from sales of industrial enterprises in Poland and Germany, %
Source: elaborated by the authors based on ZEW (2020).

ment in the industry. Theoretically, this hypothesis is substantiated by the fact that the introduction of innovations is accompanied by an increase in the level of manufacturability, automation of production processes, and, thus, the speed and quality of manufactured products, improving the organisation of labour. This, in turn, allows to significantly expand the range of industrial products and, thus, provides the emergence of new industries in related sectors of industry and economy and contributes to the expansion and strengthening of intersectoral ties. As a result, these processes will require new skills. New specialities will help create new jobs and boost employment.

An additional theoretical substantiation of this hypothesis is the results of Polish research by Piłka (2019, p. 28) regarding the impact of innovations on the development of the automobile industry. The research states: "The innovations introduced in the enterprise contribute to the increase and acceleration of production and employment growth". Also, Karpińska (2018, p. 227) used the examples of Podlaskia to substantiate that "...the influence of innovation on employment is connected to so-called creative destruction, which means that on the one hand innovation destroys existing working positions, but on the other hand it creates new ones — more specialised and requiring new knowledge". On the basis of surveys of enterprises in Podlaskia, Karpińska and Protasiewicz (2019) found that innovations demand had a positive effect on employment. In addition, 60 % of respondents argued that innovation promoted employment.

Analytical substantiation of the proposed hypothesis was performed using a correlation-regression analysis. Calculated on the basis of actual CSO data for 2008–2018, the correlation coefficient between the level of product innovation (in this study, assumed as the share of the net income from sales of innovative products in the net sales revenue of industrial enterprises in general) and employment in the industry (in this study, assumed as the share of the industry in the average employment of the economy) showed high interdependence (r=0.78) between these variables in Poland (Table 6). There is a direct linear relationship between the selected indicators.

To calculate the impact of product innovation on employment in the Polish industry, a linear regression equation is constructed:
Equation (2), based on its statistical characteristics, has a very high significance (Fig. 2). The interpretation of this equation, according to the actual data, confirmed its ability to predict employment in the Polish industry with an accuracy of 99.2 %.

Using the interpretation of the linear regression equation (2), it is determined that with increasing

$$Y = 0.27423x + 25.11183 \quad (2)$$

where:

Y- the share of the industry in the average employment of the Polish economy (employment in the industry);

x - the share of the net income from the sale of innovative products in the net income from the sale of Polish industrial enterprises in general (the level of product innovation).

level of innovation of industrial products (x) to 1 pp, the average employment in the Polish industry (Y) will increase to 0.71 pp. In 2018, the innovativeness of the Polish industry products was 9.9 %, and the average employment in the Polish industry was 27.39 %. If the innovation of industrial products is increased to 1 pp (up to 10.9 %), the employment rate with an accuracy of 99.2 % will amount to 28.10 %, which is an increase to 0.71 pp.

Thus, there is a high direct relationship between the values of the industry's share in average employment and the values of the share of the net income from sales of innovative products in the net income from sales of industrial enterprises in general (as evidenced by statistical substantiation using the example of the Polish industry and confirmed the hypothesis that increasing the level of product innovation contributes to increased employment in the industry).

The second hypothesis states that the growth of product innovation contributes to an increase in the gross monthly wages of industrial workers. The theoretical justification for this hypothesis is that for products with a low degree of innovation and processing raw materials, GVA does not provide high marginal revenue nor financial prerequisites for increasing wages. Instead, an increase in the level of product innovation contributes to an increase in its value, demand, gross margin and financial prerequisites for increasing the gross average wage of industrial workers.

The relationship between the change in the level of product innovation and the change in the gross average monthly salary of a Polish industrial worker is generally graphically close to a parabola (Fig. 3).

The high closeness of the relationship (r=0.76) was determined by the correlation coefficient based on CSOP (2020) data for 2008–2018 between the

Regression Summary for Dependent Variable: Var1 (Spreadsheet31) R= 0.75330945 RI= 0.56747513 Adjusted RI= 0.51941681 F(1.9)=11.808 p

	b*	Std.Err. - of b*	b	Std.Err. - of b	t(9)	p-value
Intercept			25.11183	0.766818	32.74809	0.000000
Var2	0.753309	0.219222	0.27423	0.079805	3.43628	0.007434

Fig. 2. Statistical characteristics of the linear one-factor regression equation of the impact made by the level of product innovation on average employment in the Polish industry
Source: elaborated by the authors based on CSOP (2020).

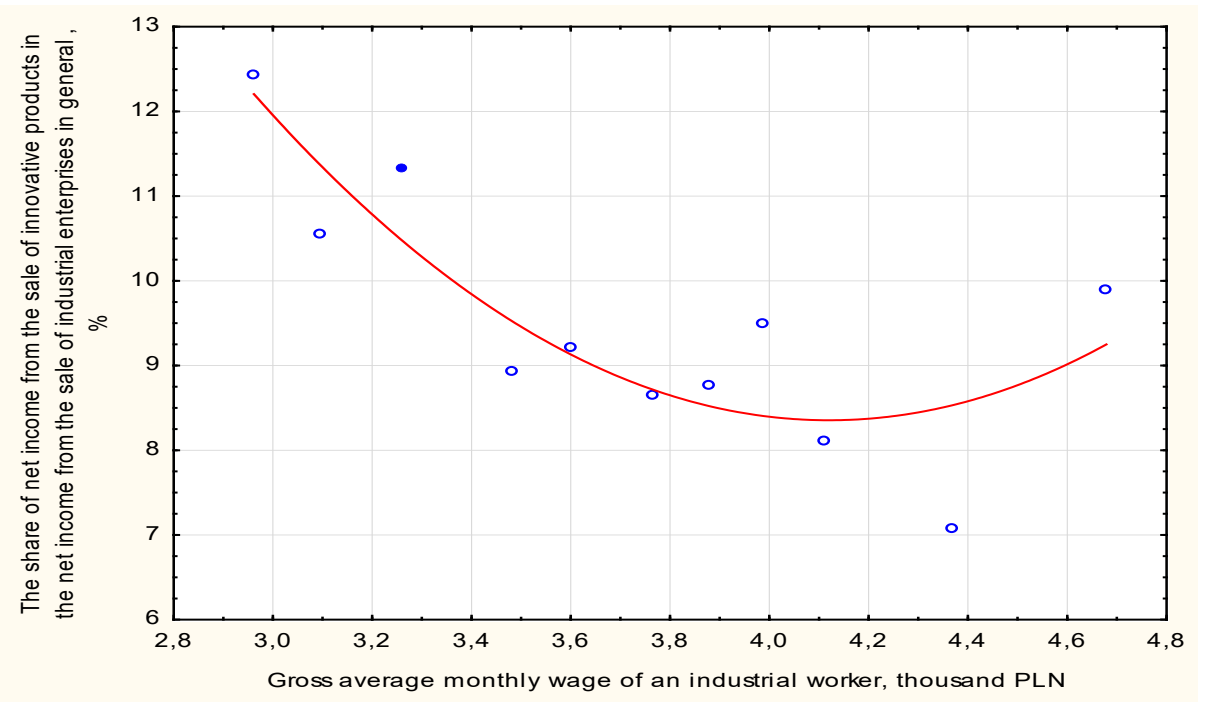

Fig. 3. Relationship between the share of the net income from the sale of innovative products in the net income from the sale of industrial enterprises in general and the gross average monthly wage of a Polish industrial worker
Source: elaborated by the authors based on CSOP (2020).

values of the index of gross average wages of industrial workers and the index of the share of the net income from sales of innovative products in the net sales revenue of industrial enterprises in general (Table 7).

The constructed quadratic equation of nonlinear regression (3) has a high significance, confirmed by its corresponding statistical characteristics (Fig. 4):

In equation (3), index values of indicators are used to achieve high forecasting accuracy, which could not be obtained when constructing a regression based on the actual data of the considered indicators.

Based on all actual data, the accuracy in the interpretation of this equation is ≈99.9 %, which allows high-precision forecasting of changes in the gross average monthly salary under the changing innovation level of the Polish industry.

$$M = -0.981666z + 0.480878z2 + 1.536449 \quad (3)$$

where:

M - the index of the gross average monthly wages of industrial workers in Poland;

z - the index of the share of the net income from sales of innovative products in the net income from sales of Polish industrial enterprises in general.

The interpretation of the quadratic nonlinear regression equation (3) suggests that with the increase in the innovation of industrial products (z) to 1 pp, the gross average monthly wage of a Polish industrial

Tab. 6. Input data for calculating the linear regression equation of the impact of the level of product innovation on employment in the Polish industry, %

Year	Employment in the industry (the share of the industry in the average employment of the economy) (*Y*)	Level of product innovation (the share of the net income from sales of innovative products in the net sales revenue of industrial enterprises in general) (*x*)
2008	29.30	12.43
2009	27.90	10.56
2010	27.70	11.34
2011	27.70	8.93
2012	27.50	9.22
2013	27.50	8.65
2014	27.60	8.78
2015	27.50	9.50
2016	27.40	8.12
2017	27.40	7.08
2018	27.39	9.90

Source: elaborated by the authors based on CSOP (2020).

Tab. 7. Input data for the construction of a regression model of the impact of changes in the level of product innovation on the change in gross average monthly wages of the Polish industry

Year	Gross average monthly wage of an industrial worker, thousand PLN	Share of net income from sales of innovative products in the net income from sales of industrial enterprises in general, %	Index of gross average monthly wage of an industrial worker (*M*)	Index of the share of the net income from sales of innovative products in the net income from sales of industrial enterprises in general (*z*)
2008	2.96	12.43	x	x
2009	3.09	10.56	1.04	0.85
2010	3.26	11.34	1.05	1.07
2011	3.48	8.93	1.07	0.79
2012	3.60	9.22	1.03	1.03
2013	3.76	8.65	1.05	0.94
2014	3.88	8.78	1.03	1.02
2015	3.98	9.50	1.03	1.08
2016	4.11	8.12	1.03	0.85
2017	4.37	7.08	1.06	0.87
2018	4.68	9.90	1.07	1.29

Source: elaborated by the authors based on CSOP (2020).

Regression Summary for Dependent Variable: Var1 (Spreadsheet8) R= 0.72579317 RI= 0.52677573 Adjusted RI= 0.39156879 F(2.7)=3.8961 p						
	b*	**Std.Err. - of b***	**B**	**Std.Err. - of b**	**t(7)**	**p-value**
Intercept			1.536449	0.180922	8.49235	0.000062
Var2	-8.92948	3.242810	-0.981666	0.356500	-2.75362	0.028355
V22**	9.01979	3.242810	0.480878	0.172886	2.78147	0.027240

Fig. 4. Statistical characteristics of the quadratic, nonlinear equation of the impact made by product innovation changes on the change in gross average monthly wages of Polish industry workers
Source: elaborated by the authors based on CSOP (2020).

worker (M) will increase to 4 %. If the actual value of the level of innovation of Polish industry products (which in 2018 was 9.9 %) is increased to 1 pp (up to 10.9 %), the actual gross average monthly salary in the same year will increase to 190 (from PLN 4.68 thousand to 4.87 thousand) or 4 %. The accuracy of this predictive interdependence is very high (≈99.9 %), and the obtained result is significant.

Thus, there is every reason to believe that the hypothesis regarding the growth of product innovation contributing to an increase in gross monthly wages of industrial workers is theoretically, analytically and statistically confirmed and substantiated.

The irrational structure is the main reason for the generally low level of innovation in the Polish industry compared to other EU countries. To optimise the structure of the industrial sector of the economy by increasing the level of product innovation, i.e., achieving the desired share of sold innovative products in the industry in general, the authors developed an economic–mathematical model, the prototype of which is described in detail and tested in optimising the structure of the Polish industry (Ishchuk, Sozanskyy & Pukała, 2020). The optimisation model (4) is deterministic and reflects the presence of functional dependence, i.e., a change in the value of one indicator necessarily changes the value of another. The dependence exists between the dynamics in the share of individual industry segments in the structure of sold industrial products and the change in the share of innovative products in the volume of sold industrial products:

As already mentioned, the target function of optimisation is to increase the actual innovation value of industrial products to the desired level, and in this case, the share of innovative products in sales, which corresponds to the share of net sales of innovative products in the net sales of industrial enterprises.

When building the optimisation model (4), a set of criteria and constraints was formed:

$$\frac{I}{P}=\frac{I\left(\frac{I}{I}\right)\left(\left(\frac{I_q}{I}+\frac{I_m\left(\frac{I_m}{I_m}\right)\left(\frac{I_{m_1}}{I_m}+\frac{I_{m_2}}{I_m}+\ldots+\frac{I_{m_{23}}}{I_m}\right)}{I}+\frac{I_e}{I}+\frac{I_w}{I}\right)\right)}{P\left(\frac{P}{P}\right)\left(\left(\frac{P_q}{P}+\frac{P_m\left(\frac{P_m}{P_m}\right)\left(\frac{P_{m_1}}{P_m}+\frac{P_{m_2}}{P_m}+\ldots+\frac{P_{m_{23}}}{P_m}\right)}{P}+\frac{P_e}{P}+\frac{P_w}{P}\right)\right)}\rightarrow opt \quad (4)$$

where:

I - the innovative products of the industry;

P - the sold industrial products;

I_q - the innovative products of the extractive industry;

I_m - the innovative products of the processing industry;

$I_{m_1}.I_{m_2}.I_{m_{23}}$ - the innovative products of 23 manufacturing industries;

I_e - the innovative products for the supply of electricity, gas, ste and air conditioning;

I_w - the innovative water supply products; sewerage, waste management

P_q - the sold products of the extractive industry;

P_m - the sold products of the processing industry;

P_{m_1} P_{m_2} $P_{m_{23}}$ - the sold products of 23 manufacturing industries

P_e - the sold products for the supply of electricity, gas, steam, air conditioning, and water supply;

P_w - the sewerage, waste management.

1. The sum of shares of 4 segments of industrial activity in the structures of innovative products and sold industrial products is equal to 1;

2. The sum of the shares of 23 industries in the structures of innovative products and sold products of the processing industry is equal to 1;

3. The value of product innovation of 4 segments of industrial activity and 23 industries of the processing industry should grow. The shares should grow for those industries in which the actual value of product innovation exceeds the industry average in the structures of innovative products and sold industrial products.

The optimisation model (4) is solved by the method of linear programming. The target functional

Tab. 8. Optimisation of the Polish industry structure by the criterion of product innovation

PRODUCTION	FACTUAL DATA (2018)			OPTIMISED DATA			DEVIATION OF OPTIMIZED DATA TO ACTUAL		
	STRUCTURE OF SOLD INDUSTRIAL PRODUCTS	STRUCTURE OF INNOVATIVE PRODUCTS	SHARE OF INNOVATIVE PRODUCTS IN THE VOLUME OF SALES	STRUCTURE OF SOLD INDUSTRIAL PRODUCTS	STRUCTURE OF INNOVATIVE PRODUCTS	SHARE OF INNOVATIVE PRODUCTS IN THE VOLUME OF SALES	STRUCTURE OF SOLD INDUSTRIAL PRODUCTS	STRUCTURE OF INNOVATIVE PRODUCTS	SHARE OF INNOVATIVE PRODUCTS IN THE VOLUME OF SALES
Industry	**100.00**	**100.00**	**9.9**	**100.00**	**100.00**	**23.6**	**x**	**x**	**13.7**
Mining and quarrying	3.59	0.11	0.3	2.20	0.09	0.9	-1.4	0.0	0.6
Of which mining of coal and lignite	1.72	0.03	0.2	0.78	0.03	0.8	-0.9	0.0	0.6
Manufacturing	86.02	99.03	11.7	**87.40**	**99.20**	26.8	1.4	0.2	15.1
Manufacture of food products	14.04	7.62	5.5	9.20	7.70	19.7	-4.8	0.1	14.2
Manufacture of beverages	2.22	1.40	6.4	2.63	1.19	10.7	0.4	-0.2	4.3
Manufacture of tobacco products	0.74	0.55	7.5	0.98	0.45	10.9	0.2	-0.1	3.4
Manufacture of textiles	0.88	0.89	10.3	1.20	0.75	14.7	0.3	-0.1	4.4
Manufacture of wearing apparel	0.32	0.16	5.1	0.34	0.13	9.1	0.0	0.0	4.0
Manufacture of leather and related products	0.27	0.68	25.9	0.32	0.57	41.7	0.0	-0.1	15.8
Manufacture of products of wood, cork, straw and wicker	2.04	2.09	10.4	2.53	1.81	16.9	0.5	-0.3	6.5
Manufacture of paper and paper products	3.07	4.51	14.9	3.21	4.19	30.8	0.1	-0.3	15.9
Printing and reproduction of recorded media	0.84	0.70	8.4	0.85	0.58	16.0	0.0	-0.1	7.6
Manufacture of coke and refined petroleum products	6.97	10.03	14.6	4.87	4.02	19.5	-2.1	-6.0	4.9
Manufacture of chemicals and chemical products	4.54	3.45	7.7	5.40	3.11	13.6	0.9	-0.3	5.9
Manufacture of pharmaceutical products	0.81	0.78	9.8	1.00	0.65	15.3	0.2	-0.1	5.5
Manufacture of rubber and plastic products	6.26	4.08	6.6	6.51	3.74	13.6	0.3	-0.3	7.0
Manufacture of other non-metallic mineral products	3.91	2.04	5.3	3.95	1.77	10.5	0.0	-0.3	5.2
Manufacture of basic metals	4.31	1.70	4.0	4.35	1.46	7.9	0.0	-0.2	3.9
Manufacture of metal products	6.29	4.77	7.7	6.35	4.47	16.6	0.1	-0.3	8.9
Manufacture of computer, electronic and optical products	2.77	6.01	22.0	2.80	5.82	49.1	0.0	-0.2	27.1
Manufacture of electrical equipment	4.41	11.93	27.4	5.36	13.40	59.0	1.0	1.5	31.6
Manufacture of machinery and equipment n.e.c.	3.39	4.98	14.9	4.50	4.68	24.6	1.1	-0.3	9.7
Manufacture of motor vehicles, trailers and semi-trailers	11.24	22.51	20.3	13.20	31.54	56.4	2.0	9.0	36.1
Manufacture of other transport equipment	1.58	3.49	22.4	2.19	3.15	33.9	0.6	-0.3	11.5
Manufacture of furniture	2.79	1.87	6.8	2.80	1.61	13.6	0.0	-0.3	6.8
Other manufacturing	0.72	0.32	4.5	0.74	0.26	8.4	0.0	-0.1	3.9
Repair and installation of machinery and equipment	1.62	2.47	15.5	2.10	2.16	24.3	0.5	-0.3	8.8
Electricity, gas, steam and air conditioning supply	8.00	0.39	0.5	8.02	0.32	1.0	0.0	-0.1	0.5
Water supply, sewerage, waste management and remediation activities	2.38	0.47	2.0	2.39	0.39	3.8	0.0	-0.1	1.8

Source: elaborated by the authors based on CSOP (2020).

of optimising the industry structure is the level of product innovation, at which the gross average monthly wage of a Polish industrial worker will double and approach the average EU level. The numerical expression of the target functional is calculated using the interpretation of equation (2). It was established that for the gross average monthly wage in the Polish industry to double compared to the actual data of 2018 and amount to PLN 9.36 thousand (or about EUR 2.300), the level of innovation in industrial products should be 23.60 %, i.e., increase by 2.4 in times (from 9.9 % in 2018). Thus, the target functional of optimisation of the structure of the Polish industry (according to model (4)) is the achievement of product innovation at the level of 23.60 %.

According to the results of the calculation of model (4), considering the defined limitations, the optimised structure of sold products in general and innovative products, in particular, is obtained (Table 8).

According to the results, the Polish industry will be able to reach the level of product innovation of 23.60 % and increase the gross average monthly wage of workers if the structure of sales increases the share of production, for which the country has sufficient raw materials and innovation potential. These are, in particular, the production of the processing industry (textile, wood processing, furniture, and chemical) and certain types of mechanical engineering (highlighted in colour in Table 8).

In addition, the share of raw materials production with relatively low innovation potential, by definition, should decrease in the structure of the Polish industry. These are, in particular, manufactures of food products, coke and refined petroleum products, mining and quarrying, of which mining of coal and lignite. Such structural changes would increase the innovativeness of Polish industry products in general, and mainly, mechanical engineering products.

Conclusions

The theoretical contribution of the study is as follows. The approach to assessing the innovation of regional industries has been developed. Its peculiarity is the simultaneous analysis of direct indicators of product innovation and interrelated indicators that provide economic prerequisites for innovation and their economic results (indicators of investment activity, productivity, and profitability). In addition, the difference of this approach is in the use of the dynamics indicators (indices) together with current state indicators.

The theoretical assumptions of individual researchers regarding the relationship between innovation and wages and employment are mathematically substantiated and characterised.

An economic-mathematical model for optimising the structural parameters of industry according to the criterion of innovation has been developed and tested on the example of the Polish industry.

The results of the author's method of assessing the efficiency of the industrial sector at the macro and meso levels revealed signs of regional structural transformation of the Polish industry in the direction of forming potentially new industrial centres focused on increasing product innovation and productivity. In particular, a comprehensive assessment of investment, innovation and labour activity, as well as the profitability of the Polish industry, identified two key trends in the industrial development of voivodships: the gradual loss of industrial potential of classical industrial regions and, conversely, its increase in potentially new industrial regions.

The industrial sector of the economy of classical industrial regions is mainly characterised by high values of current indicators, but at the same time, low values of dynamics. This trend is most pronounced in the indicators of labour and innovation activity. On the other hand, other types of regions (those that increase industrial potential) are characterised by opposite features — relatively small values of actual indicators of industrial functioning, but high positive dynamics of these indicators and, especially, product innovation and productivity.

Further research has shown that one of the weaknesses of the Polish industry is low product innovation. The latter has a significant impact on the main economic and social indicators of this sector of the economy. The importance of innovation activity was confirmed by the results of correlation-regression analysis, which proved the adequacy of the hypothesis regarding the growth of product innovation contributing to increased employment in the Polish industry. The results of the interpretation of the constructed one-factor regression model proved the possibility of its application in forecasting employment in the Polish industry. Thus, it can be stated with high accuracy that the growth of product innovation to 1 pp will increase employment in the Polish industry to 0.71 pp.

The importance of innovation activity to ensure socio-economic development is confirmed by the

second hypothesis that the growth of product innovation has a positive effect on the growth of gross average monthly wages. The developed quadratic nonlinear regression allows to highly accurately predict the change in the gross average monthly wage in the industry when the level of product innovation changes. The interpretation of this model allowed forming a statement that with the growth of product innovation to 1 pp, gross monthly wages in the Polish industry will increase to 4 %.

One of the basic conditions for increasing innovation activity is the structural transformation of the industry. To optimise the structure of the industrial sector of the Polish economy according to the criterion of increasing the level of product innovation, an economic and mathematical optimisation model was developed and solved using the method of linear programming. The target functionality of this model is the level of product innovation, at which the gross average monthly wage of Polish industry workers will double (to the EU average).

Further research will focus on modelling the impact of other factors, primarily labour productivity and investment (internal and external), on the level of innovation of industrial products.

Acknowledgements

The publication of the article for 11th International Conference on Engineering, Project, and Production Management - EPPM2021 was financed in the framework of the contract no. DNK/SN/465770/2020 by the Ministry of Science and Higher Education within the "Excellent Science" programme.

Literature

Adamowicz, M. (2021). The Potential for Innovative and Smart Rural Development in the Peripheral Regions of Eastern Poland. *Agriculture*, *3*(11), 188. doi: 10.3390/agriculture11030188

Brezdeń, P., & Spallek, W. (2009). Efektywność firm korporacyjnych o dobrym standingu w województwie dolnośląskim w ujęciu przestrzennym [Effectiveness of corporations with good standing in the Lower Silesian Voivodship in a spatial perspective]. *Studies of the Industrial Geography Commission of the Polish Geographical Society*, 14, 81-94.

Brezdeń, P., & Spallek, W. (2013). Spatial Differentiation of the Level of Innovation of Regional Economy of Lower Silesian Voivodeship. *Studies of the Industrial Geography Commission of the Polish Geographical Society*, *23*, 9-25. doi: 10.24917/20801653.23.1

Čapek, J. (2016). Structural Changes in the Czech Economy: A DSGE Model Approach. *Prague Economic Papers*, *25*(1), 37-52. doi: 10.18267/j.pep.535

Central Statistical Office of Poland (CSOP). (2020). Retrieved from http://stat.gov.pl

Chybowska, D., Chybowski, L., & Souchkov, V. (2018). Is Poland an Innovative Country? *Management Systems in Production Engineering*, *1*(26), 35-41. doi: 10.2478/mspe-2018-0006

Czech, A., & Lewczuk, J. (2016). Taxonomic and Econometric Analysis of Road Transport Development in Poland – The Voivodship Approach. *Engineering Management in Production and Services*, *8*(3), 79-88. doi: 10.1515/emj-2016-0026

Dąbrowski, D. (2018). Different sources of market information and product innovativeness. *Economics and Business Review*, *18*(3), 7-23. doi: 10.18559/ebr.2018.3.2.

Gajda, W. (2016). A comparative analysis of the innovativeness of Polish industry from 2008–2014. *Finanse, Rynki Finansowe, Ubezpieczenia*, *4*(82/2), 35-45. doi: 10.18276/frfu.2016.4.82/1-03

Godinho, M., Mendonça, S., & Pereira, T. (2005). Towards a taxonomy of innovation systems. *Working Papers Department of Economics from ISEG – Lisbon School of Economics and Management, Department of Economics, Universidade de Lisboa*, 13, 1-43. Retrieved from https://econpapers.repec.org/paper/iseisegwp/wp132005.htm

Golejewska, A. (2018). Innovativeness of Enterprises in Poland in the Regional Context. *Journal of Entrepreneurship, Management and Innovation*, *14*(1), 29-44. doi: 10.7341/20181412

Hellwig, Z. (1968). Zastosowanie metody taksonomicznej do typologicznego podzialu krajow ze wzgledu na poziom ich rozwoju oraz zasoby i strukture wykwalifikowanych kadr [The typonomic method used for countries typological due to their level of development, resources and qualified cadres structure]. *Przeglad Statystyczny – Statistical Review*, *15*(4), 307-327.

Ishchuk, S. O. (2018). Rating of the regions of Ukraine by the level of competitive advantages of industry. *Economics and law*, *2*(50), 92-102. doi: 10.15407/econlaw.2018.02.092

Ishchuk, S., Sozanskyy, L., & Pukała, R. (2020). Optimization of relationship between structural parameters of processing industry as a factor influencing its effectiveness. *Engineering Management in Production and Services*, *12*(2), 7-20. doi: 10.2478/emj-2020-0008

Janiszewska, D., & Ossowska, L. (2016). Regional differences in the level of innovativeness in Poland. Annals of the polish association of agricultural and agribusiness economists. *Annals*, *18*(3), 108-113. Retrieved from https://rnseria.com/resources/html/article/details?id=179174

Karpińska, K. (2018). Innovation versus structural changes in employment in the light of the available sta-

tistical data in Podlaskie voivodeship. *Optimum. Economic Studies*, *92*(2), 227-240. doi: 10.15290/oes.2018.02.92.17

Karpińska, K., & Protasiewicz, A. (2019). Rola innowacji popytowych i podażowych w zatrudnieniu w przedsiębiorstwach województwa podlaskiego [The role of demand and supply innovations in employment in enterprises of the Podlaskie region]. *Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu*, 544(1), 61-69. doi: 10.15611/pn.2019.544.07

Kongaut, C., & Bohlin, E. (2017). Impact of broadband speed on economic outputs: An empirical study of OECD countries. *Economics and Business Review, 17*(2), 12-32. doi: 10.18559/ebr.2017.2.2

Kotowicz-Jawor, J., Pietrewicz, L, Zajfert, M., Mączyńska, E., Baczko, T., Puchała-Krzywina, E., & Grzelońska, U. (2019). *Innovativeness of Polish Economy in the Transitional Stage of Development*. Łódź, Poland: Wydawnictwo Uniwersytetu Łódzkiego. doi: 10.18778/8142-786-9

Kudełko, J. (2016). Rola przemysłu w rozwoju regionów Polski Wschodniej [The Role of Industry in the Development of Eastern Poland Regions]. *Prace Komisji Geografii Przemysłu Polskiego Towarzystwa Geograficznego* [*Studies of the Industrial Geography Commission of the Polish Geographical Society*]. *The Central European Journal of Social Sciences and Humanities*, *30*(3), 147-158.

Lubacha, J. (2019). Regional innovation systems of Polish regions. In A. P. Balcerzak & I. Pietryka (Eds.), *Contemporary Issues in Economy: Proceedings of the International Conference on Applied Economics: Economics* (pp. 226-235). Olsztyn, Poland: Institute of Economic Research. doi: 10.24136/eep.proc.2019.1

Majka, A., & Jankowska, D. (2017). Innovative Endeavors and Economic Development from the Regional Perspective. *Barometr Regionalny*, *3*(15), 29-39.

Miłek, D. & Mistachowicz, M. (2019). Innovation of the Polish Economy in comparison to European Union countries. MATEC Web of Conferences, 252. doi: 10.1051/matecconf/201925209006

Pidorycheva, I. Y., & Kovchuha, L. I. (2019). Analysis of correlation between innovative costs and volumes of realized innovative products in the industry of Ukraine. *Economy of Industry*, *3*(87), 76-102. doi: 10.15407/econindustry2019.03.076

Piłka, M. (2019). Impact of innovations on industry development on the example of the automotive industry. *Zeszyty Naukowe Wyższej Szkoły Humanitas Zarządzanie*, *20*(1), 21-31. doi: 10.5604/01.3001.0013.2417

Pla-Barber, J., & Villar, C. (2019). Governance and competitiveness in global value chains: A comparative study in the automobile and textile industries. *Economics and Business Review*, *5*(19), 3, 72-91. doi: 10.18559/ebr.2019.3.5

Sozanskyy, L. (2017). Grouping of regions of Ukraine is after level of economic activity of industry. *Journal of European Economy*, *16*(1), 121-133.

Sozanskyy, L. (2018b). Indicators of activity and efficiency of the industry of Lviv region and Podkarpackie voivodship. *SocioEconomic Problems and the State*, *1*(18), 129-136.

Sozanskyy, L. (2018a). Evaluation of the results of industry functioning in Ukraine and Poland. *Socio-economic Problems of the Modern Period of Ukraine*, *1*(129), 28-32.

Tereszczuk, M. (2015). Comparative Evaluation of the Polish Meat Industry Related to Selected Countries of the European Union. *Roczniki Naukowe Stowarzyszenia Ekonomistów Rolnictwa i Agrobiznesu, 17*(4), 319-324.

Węglarz, M. (2018). Innovation of the Polish economy in comparison with the EU member states. *Economic and Environmental Studies*, *18*(2), 971-993. doi: 10.25167/ees.2018.46.31

Weresa, M. A. (2019). Technological competitiveness of the EU member states in the era of the fourth industrial revolution. *Economics and Business Review, 19*(3), 50-71. doi: 10.18559/ebr.2019.3.4

Wich, U. (2017). Innovativeness of Poland in the Assessment of the European Union and from Regional Perspective. *Annales Universitatis Mariae Curie-Skłodowska. Oeconomia*, *H*, *1*(51), 101-111. doi: 10.17951/h.2017.51.1.101

Wlodarczyk, A. (2013). The optimization of the structure of the factors of production in the food industry in Poland – the approach based on the production function methodology. In C. B. Illes, F. Bylok, A. Dunay & L. Cichobłaziński (Eds.), *People, Knowledge and Modern Technologies in the Management of Contemporary Organizations. Theoretical and Practical Approaches* (pp. 225-239). Częstochowa, Poland: Czestochowa University of Technology.

Zakrzewska, A., & Chojnacki, P. (2020). Innovation and efficiency of food industry firms in Poland by regions. *Research Papers of Wroclaw University of Economics and Business*, *7*(64), 142-153. doi: 10.15611/pn.2020.7.11

ZEW (Leibniz Centre for European Economic Research). (2020). *Core indicators innovations.* Retrieved from https://www.zew.de/publikationen/zew-gutachten-und-forschungsberichte/forschungsberichte/innovationen/innovationserhebung/kernindikatoren

sciendo

ISMSME International Society for Manufacturing, Service and Management Engineering

received: 30 March 2021
accepted: 10 September 2021

pages: 25-36

Application of factor analysis in company management – selected examples related to competitiveness and market success

Jolanta Jurczak Grzegorz Jurczak

ABSTRACT

Factor analysis is a standard statistical technique for reducing data dimensionality, which is widely used in sociology, psychology, and demography. Also, financial and insurance institutions commonly use such a technique for marketing research. In recent years, factor analysis has been used, at the beginning rather diffidently, to analyse selected problems of business management, e.g. to troubleshoot consumer and company communication. There are some literature reports about the successful use of factor analysis in managing a company area. Nevertheless, the literature seems to lack examples with successful use of the method with a clear explanation of its rather difficult application in the field of competitiveness or potential company boost. The modest popularity of such a powerful technique in this particular field seems to be attributed mainly to the complexity of the method and its requirements concerning the data quantity. Besides, the factor analysis technique has great potential and can be used as an efficient tool to reduce the complexity of observed phenomenon or verify the accuracy of theoretical models. Therefore, the purpose of this paper is to present a vast potential of factor analysis (both exploratory and confirmatory) applied to solve various problems in company management, especially related to competitiveness and market success. Two case studies covering the subject of business management are presented to illustrate the benefits of factor analysis application. The exploratory factor analysis is exemplified by the search of factors related to the commercial success of the company, while the confirmatory technique is illustrated by a case study of the intellectual capital of the company and its factors related to competitiveness. The paper also presents the essence of the factor analysis, types of analysis, subsequent procedures, purposes, and its specific features. Finally, the applicability of the factor analysis to solve management issues and possible gain in management are discussed.

KEY WORDS

factor analysis, confirmatory factor analysis, exploratory factor analysis, management

10.2478/emj-2021-0019

Jolanta Jurczak

Faculty of Management, Warsaw University of Technology, Poland
ORCID 0000-0003-2584-6427

Corresponding author:
e-mail: jolanta.jurczak@pw.edu.pl

Grzegorz Jurczak

Institute of Fundamental Technological Research, Polish Academy of Sciences
Poland
ORCID 0000-0002-6978-8639

Introduction

Nowadays, contemporary businesses operate in an extremely volatile market, and competition is a crucial factor in the business environment. A shift of the client's preferences, which is difficult to predict, forces businesses to continue adjusting their market strategies to an irregular situation. In other words, successful companies have to take chances and avoid threats. Many variable management methods and techniques are reported in the Management Sciences

Jurczak, J., & Jurczak, G. (2021). Application of factor analysis in company management — selected examples related to competitiveness and market success. *Engineering Management in Production and Services, 13*(3), 25-36. doi: 10.2478/emj-2021-0019

(MS) literature to support businesses in their market activity. These techniques may increase business efficiency and uprate its market value, e.g. by improving the ability to adapt the current market strategy to customer demands. One of these techniques is Factor Analysis (FA) (Vincent, 1953; Mulaik, 1987), a statistical method that looks at a complex, multivariate problem and significantly reduces its complexity using a few abstractive factors instead of numerous initial variables. Once the problem is reduced and described by abstractive common factors, the company can focus on relevant factors.

1. Literature review

No doubt, statistical data is a powerful source of marketing information, and factor analysis (FA) as a data mining technique plays an essential role in many areas of a running business, especially related to the customers and their market behaviour (Brown, 2006; Czopek, 2014). An FA-based statistical analysis reveals the hidden structure of the market phenomenon, which may support marketing departments in decision-making based on the balance of cost, risk and opportunities. Also, adequate FA research may support intellectual capital management, leadership evaluation, innovation policy, inventory control and the rise of enterprise goodwill. Despite the possible benefits, the FA technique seems to be still underrated and underutilised in the MS field. In contrast, FA is a very widespread and noted technique within many other branches of science, e.g. social and psychological sciences and marketing research (Thurstone, 1947; Nawojczyk, 2002; Brown, 2006; Cortés Sánchez & Grueso Hinestroza, 2017; Chidambaram et al., 2013; Ludwikowska, 2021; Warter & Warter, 2017). The reason may be related to the lack of statistical awareness, laborious data collection, computational complexity, and problematic interpretation of abstractive factors. Also, relatively modest literature repertory offering straight guidance on applying FA to solve the problem within business management does not help to correct the situation. Nevertheless, the literature still has some reports dealing with complex management problems based on FA studies. For example, Cabuñas (2019) used the Exploratory Factor Analysis (EFA) to deal with a cost overrun in construction projects. Hawrysz (2019) studied the role of dynamic abilities on the performance of e-administration using the Confirmatory Factor Analysis (CFA). Renault (2018) analysed the risks management methods among small and medium companies. Wipulanusat (2017) used EFA to identify the leadership styles related to innovativeness in Australian Public Services. In the case of Polish companies, Jaskóła (2014) used EFA to check the main business success factors in chemical and structural companies. Jurczak (2012) used CFA to study intellectual capital factors which may create a competitive advantage in the market. Staniec (2012) used factor analysis to identify crucial problems for management systems development. Łobos (2011) dealt with income, profit, and goodwill as a universal benchmark of management success. Maciejewski (2011) studied consumer risk within the tourist industry. Zgrzywa-Ziemak (2009) dealt with the learning ability of companies.

Consequently, FA can also be used to a significant effect in management science. The FA application to deal with empirical research within MS allows determining an accurate scheme of mutual correlation between a phenomenon constituent (objects) and an accurate diagnosis about the model and its behaviour, despite the complexity of the problem. Statistical prediction resulting from FA can improve the efficiency of a company's choices in investment, finance, cost planning, risk management, intellectual capital management, leadership style, employee attitude and behaviour, client attitude, the flow up to stores or market value creation. FA is especially efficient in the case of complex problems with many possible factors that affect the behaviour of the phenomenon. As FA allows to determine the impact of each factor, the company can focus on several most important factors and thereby reduce the complexity of the problem. Such complexity is typical for management problems, especially related to learning, development, competitiveness, and success of the company in the market. Also, issues related to the measurement of intangible resources are difficult to quantify, and numerous factors may appear to generate a complicated, cross-correlated pattern. Table 1 provides the selected literature reports on applying the factor analysis addressing management problems related to the market effectiveness, competitiveness or market success.

This paper presents examples of successful FA applications. It uses Polish companies as an example to show how to apply FA to increase competitiveness or potential. The application of the EFA technique to solve management problems is illustrated presenting the study of main factors contributing to the success in the market by Jaskóła (2014). The verification of

Tab. 1. Diversification of the factor analysis application (EFA/CFA) to company management problems related to the market effectiveness, competitiveness or market success

Author (Year)	EFA / CFA application in management
D. Leończuk (2021)	Factors affecting the level of supply chain performance and its dimensions in the context of supply chain adaptability (CFA)
M.A. Hedhili, S. Boudabbous (2020)	FA analysis of competence management in companies to develop and enhance employees' skills
K. Na-Nan, S. Saribut (2020)	Validation of employees' self-leadership using exploratory and confirmatory factor analysis
L. Hawrysz (2019)	Effect of dynamic abilities on the e-administration operation (CFA)
P. Bartkowiak (2018)	Importance of selected stakeholders in the value creation process
B.Y. Renault, J.N. Agumbai et al. (2018)	EFA of risk management practices among small and medium contractors in Gauteng
V. Victor, J.J. Thoppan, R.N. Jeyakumar, F.M. Fekete (2018)	Factors influencing consumer behaviour and prospective purchase decisions in a dynamic pricing environment (EFA)
W. Wipulanusat, K. Panuwatwanich, R.A. Stewart (2017)	Exploring leadership styles for innovation (EFA)
P. Zaborek, P. Tomczyk, T. Doligalski (2016)	Customer analysis as a driver of financial performance in the Polish insurance industry (EFA)
D. Rojek (2016)	Study of strategic factors related to innovation management by EFA
H.S. Jung, H.H. Yoon (2016)	Effects of emotional intelligence on stress-coping styles and job satisfaction in the hospitality industry (EFA/CFA)
K. Jaskóła (2014)	Searching for roots of market success among international industrial corporations within the chemical and structural branch (EFA)
J. Jurczak (2012)	Study of factors related to the intellectual capital of the company and their role in the competitive advantage (CFA)
I. Staniec (2012)	FA application to identify factors related to management system perfection in Polish organisations
D. Gursoy, C.G.-Q. Chi, E. Karada (2012)	Generational differences in work values and attitudes among frontline and service contact employees verified through EFA
K. Łobos, M. Szewczyk (2011)	FA study of income, profit and company value as a universal success measure (effectiveness) of the company management
A. Zgrzywa-Ziemak, R. Kamiński (2009)	Study of the factors related to the organisation learning (CFA)
Ch. Burmann, S. Zeplin, N. Riley (2009)	Key determinants of internal brand management success (EFA)
D. Turker (2009)	Measuring corporate social responsibility (EFA)
R. Škrinjar, V. Bosilj-Vukšić, M. Indihar-Štemberger (2008)	FA in the impact of business process orientation on financial and non-financial performance
C. Brooke-Dobni (2008)	Measuring innovation culture in organisations (EFA)
J. Garczarczyk, M. Mocek (2006)	FA study of the quality of insurance services
C.L. Wang, P.K. Ahmed (2004)	Development and validation of the organisational innovativeness construct using CFA

Source: elaborated by the author based on Internet search (keywords: exploratory factor analysis in company management; confirmatory factor analysis in company management, Google Scholar).

the intellectual capital (IC) model and its ability to create a competitive advantage in the market done by Jurczak (2012) is described as an application of the CFA technique. The above examples cover complex matters that are difficult to measure directly, making them ideal for the factor analysis methodology.

2. Methodology

FA was initially developed and applied to deal with problems of complex human abilities. The method was proposed by Thurstone (1933) on the grounds of earlier works by Spearman (1904) and Pearson (1901). The goal of the method is to identify rather abstractive and hidden factors which constitute the problem as distinct from really measured variables. FA analyses survey data to find out hidden constructs, their mutual interrelation and complicity with measured variables. Replacing numerous initial variables with a limited set of factors makes the analysis relatively simple. Factors, contrary to initial variables, also possess a more general and universal character and may facilitate theoretical interpretation of the problem. According to specific goals of analysis, factor analysis is divided into exploratory and confirmatory branches. The goal of the exploratory analysis is to reveal the hidden structure of the phenomenon described by a set of measurable variables. It starts from scratch without the need to know the problem during the preliminary calculation; however, this knowledge is essential for interpreting results. Confirmatory analysis tests whether a set of factors specified by the theoretical model satisfyingly reproduces observed responses; thus, the technique needs the model to test its matching to the observations. The main assumption is to use a linear combination of (yet unknown) factors (including the specific factor) to reproduce the variation of initial variables. The problem is to determine these unknown factors accurately. The factor analysis methodology consists of several statistical procedures that can be group as follow:

- the input data check (the amount, completeness, and quality of the data),
- the applicability of the method check (the fitness of the data, Cronbach's alpha, Kaiser-Meyer-Olkin criterion),
- the factor estimation (the revelation of the hidden structure of the problem),
- the factor selection (the reduction of the problem's dimension),
- the factor rotation (highlighting selected factors and the depletion of others: Varimax, Biquartimax, Equamax),
- the interpretation of results.

Above, the abridged description of the method is provided while more comprehensive information is offered, e.g. by Frątczak (2009).

3. Results of searching for market success sources

Scientific research by Jaskóła aimed to identify the root of commercial success within the medium- and large-sized petroleum and construction companies, as well as their cooperative businesses located in Poland. Results were presented in his work "Geneza sukcesu. Dynamiczne zarządzanie korporacjami przemysłowymi" (Genesis of the success. Dynamic management of industry corporations; Jaskóła, 2014; in Polish). The author studied many parameters affecting company activity in the market and its development to find their relationship to commercial success. Based on the survey of executive managers, EFA showed the underlying structure of the issue and pointed out the main success factors having the highest contribution. The survey research comprised 38 variables related to the activity of various companies or their assets. Variables were initially assumed to comprise the company success in the market. The total number of respondents was 116 from 24 companies. The FA goal was to reduce the complexity of statistical data in questionnaires by lumping highly interrelated variables and revealing a more general structure of the problem. The analysis of common factors with respect to factor loadings revealed factors constituting the basis for success and information about their structure.

As is usual in the case of FA, the first step of the analysis was to check the data for correctness and usefulness for the factor analysis. The correlation matrix was calculated after the data adequacy verification for reducing the dimensionality (by Kaiser-Meyer-Olkin and Bartlet's tests). Eigenvectors of the correlation matrix were sorted according to their eigenvalues, which allows selecting an adequate number of common factors for further analysis. The application of various criteria for eigenvector selection usually results in a number of factors between 4 and 12. Initial, unrotated eigenvalues have rather low values, and in this case, only one was significantly greater than 1.0, whereas consecutive eigenvalues

Tab. 2. Factors determining the success of the company and their components

No	Common Factor	Initial Variables
I	market activity	1. product, 2. market, 4. active marketing, 11. business and economic surroundings, 17. active, sometimes an aggressive activity in the market, 24. product innovations, 27. marketing innovations
II	leader efficiency	10. management style, 19. resourcefulness of the leader, 20. creativity of the leader, 21. innovativeness of the leader, 23. openness to changes, 22. problems of the staff
III	technological innovativeness	5. advanced technologies, 13. technological surroundings, 18. technological development and product refining, 25. technological innovations, 35. IT technologies
IV	employee competence	3. peoples and systems, 6. system of values, 8. knowledge and staff competences, 9. job motivation

Source: (Jaskóła, 2014).

were just around 1.0. To bring out other eigenvalues, the Varimax rotation was used and three subsequent eigenvalues were significantly raised. Finally, four common factors were assumed as an appropriate factor set for further analysis. So, the underlying structure of the survey has four common factors loaded by initial variables (Table 2).

Theoretical senses of common factors were determined and attributed to market activity, leader and staff competences, and technological innovativeness. To verify mutual variable-factor interrelations, factor loadings were examined (Table 3). Typically, the cut-off point for loading meaningfulness is 0.7 (0.6 in some cases). The analysis of factor loadings allowed matching 22 of the initial 38 variables to explain the structure of the phenomenon. The cumulative variation reproduced by the underlying structure consisting of four common factors is about 50% - 59% of the initial variance (the result depends on the assumed methodology). The factor-related percentage explanation of the initial variation was equal, respectively, I:16-18%, II:12-15%, III:11-14%, IV:10-12%.

Further studies proved the existence of a strong relationship between the first factor (market activity) and subsequent factors, especially in the case of leader efficiency (factor II) and employee competence (factor III), see Table 4. It can be easily explained as a mutual relationship between market activity, quality of the leadership and competences of the staff. An opposite relationship also exists as a skilled leader by different actions or professional staff development may improve the employer competitiveness, and therefore, lead to the success in the market. Also, employee competence expressed by skilled staff able to handle innovative products may stimulate the company's development by reaching customer expectations. Also, the market activity depends on technological innovativeness and vice versa. Such a relationship can be explained by the role of technological advances and their practical implementation, allowing to reach a competitive advantage in the market. Technological innovativeness also affects leadership efficiency by providing efficient tools for production management on the one hand, and on the other hand, requiring continuous professional development of the executive management to handle these new technologies.

The commercial success of examined companies has been generally attributed to the management activity and their multifold actions, continuously increasing the company's competitiveness and streamlining market activity. The commercial success was also stimulated by a significant contribution of competent staff and continuous investments in and implementation of new technologies.

Tab. 3. Selected variables, their factor loadings, and the cumulative variation (the principal component method after the Biquartimax rotation)

No	Initial Variable	Factor I	Factor II	Factor III	Factor IV
1.	product,	0.750			
2.	market,	0.775			
3.	peoples and systems,				0.770
4.	active marketing,	0.751			
5.	advanced technologies,			0.740	
6.	system of values,				0.834
8.	knowledge and staff competences,				0.792
9.	job motivation,				0.705
10.	management style,		0.737		
11.	business and economic surroundings,	0.731			
13.	technological surroundings,			0.730	
17.	active, sometimes an aggressive activity in the market,	0.764			
18.	technological development and product refining,		0.716	0.811	
19.	resourcefulness of the leader,		0.746		
20.	creativity of the leader,		0.742		
21.	innovativeness of the leader,		0.753		
22.	problems of the staff,		0.689		
23.	openness to changes,	0.731			
24.	product innovations,			0.755	
25.	technological innovations,	0.728			
27.	marketing innovations,			0.695	
35.	IT technologies				
	Cumulative variation: 58.92%	18.32%	14.76%	13.63%	12.21%

Source: (Jaskóła, 2014).

Tab. 4. Relationships between common factors

Factor	Factor	Interrelation measure
market activity	leader efficiency	0.180
market activity	technological innovativeness	0.120
market activity	employee competence	0.170
leader efficiency	technological innovativeness	0.155
leader efficiency	employee competence	0.092
technological innovativeness	employee competence	0.054

Source: (Jaskóła, 2014).

4. Results of the intellectual capital's ability to gaining competitive advantage

The ability of the company's IC to affect its competitiveness in the market may be studied by factor analysis as well to reveal underlying constructs governing the problem and interpret their general meaning. As stated above, in the case of analysis from scratch, exploratory techniques should be used. However, to verify the already assumed model which describes observed cases, CFA should be used instead. The presented example concerns the confirmatory technique used to verify the already assumed model of the company's IC and its impact on competitive advantage in the market. Empirical studies were conducted by Jurczak (2012) on the grounds of survey research of 186 Polish consulting firms. The survey allowed to create an initial theoretical IC model and propose the model describing its market mechanism affecting the competitiveness. At first, a preliminary EFA analysis was conducted to give a theoretical background for an adequate model of the IC ability to gain competitive advantage.

According to the rules, the reliability of test scores and the internal scale consistency were verified at the beginning of the EFA analysis. Next, Cronbach's alpha, KMO, and Bartlet's measures were calculated. The revealed hidden structure of the phenomenon allows constructing a theoretical model based on four IC components boosting competitive advantage, namely, knowledge and skills of employees, mutual trust and cooperation, communication processes within the company, and public image and reputation of the company. Figure 1. shows a simplified path model of the IC ability to gain competitive advantage with subsequent factor loadings on the basis of an exploratory analysis. A full theoretical path model of the IC ability to gain competitive advantage is pre-

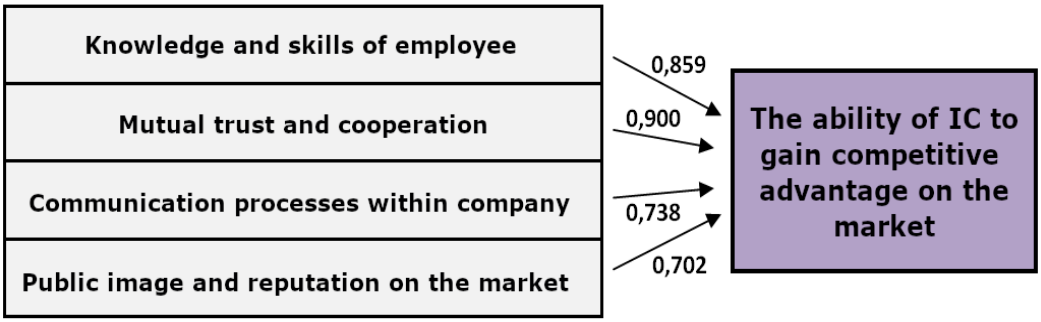

Fig. 1. Simplified path model of the IC ability to gain competitive advantage with factor loadings
Source: (Jurczak, 2012).

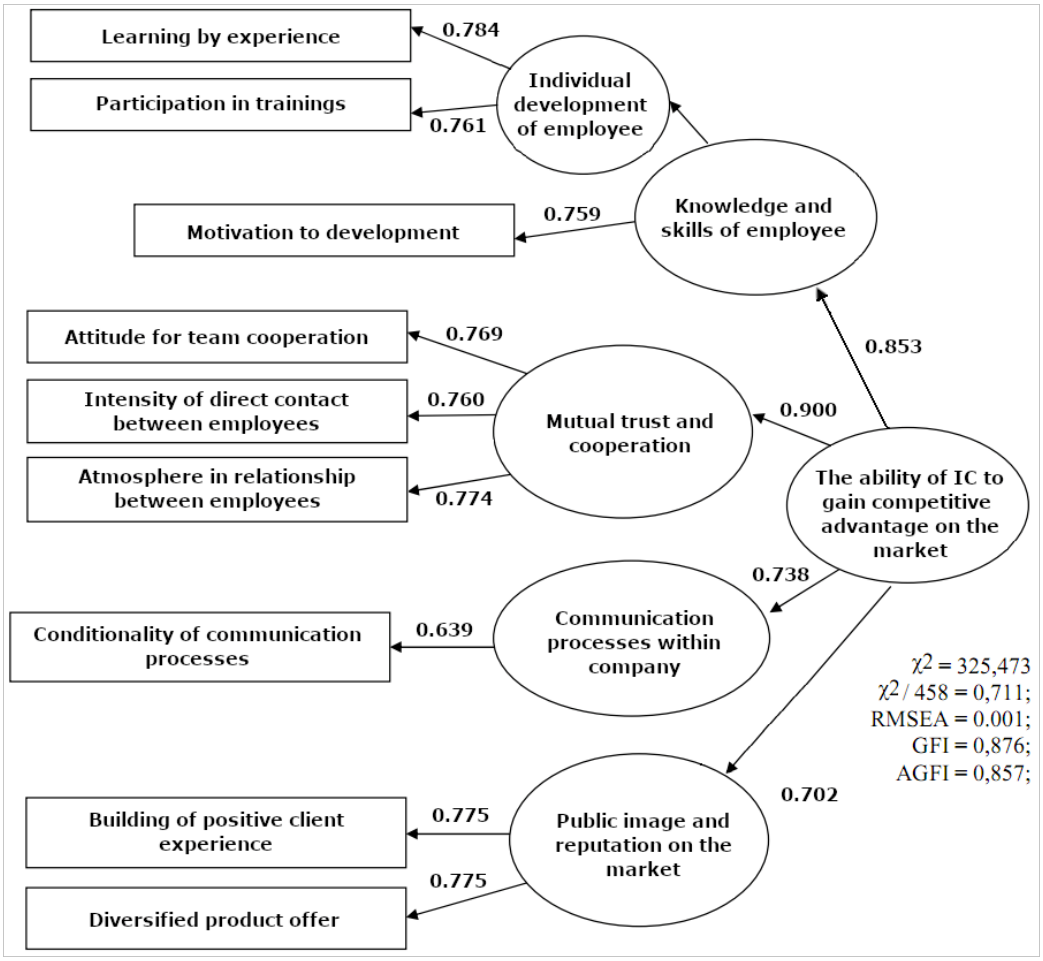

Fig. 2. Theoretical path model of the IC ability to gain competitive advantage with calculated fitting indices and factor loadings
Source: (Jurczak, 2012).

sented in Figure 2. Each factor was described by a basic hypothesis and more detailed specific hypotheses. Table 5 provides the structure of the problem based on common factors, related initial variables with options, and research hypotheses.

Next, CFA was carried out to verify the accuracy of the assumed model. To test the accuracy of the proposed model, CFA uses structural equation modelling and checks if factor loadings confirm the assumed relationships between measured variables

and underlying factors. The hypothesised model is tested against observed variables, and the analysis also demonstrates the relationship between respective factors. To quantitatively evaluate the accuracy of the model and its ability to reproduce the initial data variance, the following fit indices were used:

- chi square statistic — $\chi 2$/degree of freedom (dof),
- Steiger-Lind's root mean square error of approximation — RMSEA,
- Joreskog's goodness of fit index — GFI,
- adjusted goodness of fit index — AGFI.

General fitting parameters of the hypothesised model are presented in Figure 2, next to the path model, while partial fitting measures in the case of separated factors within the model are presented in Table 6. The statistical analysis of particular factors that are assumed in the proposed model shows that the fitting quality is relatively high, despite the used fitting index. The basic $\chi 2$/dof index shows that the proposed model has an excellent fit with polling data.

Tab. 5. Assumed hypotheses and common factor structure connected with initial variables related to the IC ability to gain competitive advantage

Factor	Basic hypothesis	Specific hypothesis	Variables	Options
knowledge and skills of employees	**H1**: The more profound is knowledge and higher skills of employees, the higher ability of the company's IC to gain a competitive advantage in the market	**H1_1**: The faster employees gain the knowledge and improve skills, the higher is the knowledge and skills of employees	Learning by experience	Less experienced employees are mobilised to observe more experienced employees
				More experienced employees are trainers and advisers for less experienced employees
				Changing the occupation in the enterprise deepens the knowledge and expedites the development of skills of employees
		H1_2: The more intense is the motivation of employees for professional development and improvement of skills, the higher is the knowledge and skills of employees	Participation in training	Training in the occupation
				Discussion within the team
				Case-study
				Lectures
			Motivation to develop	Fixing different and complicated tasks
				Granting a bonus for improving processes and products of the company
				Participation in formulating the purpose of the enterprise
mutual trust and cooperation	**H2**: The higher is the value of the relationship based on mutual trust and cooperation, the higher is the IC ability to gain a competitive advantage in the market	**H2_1**: The more appreciation is given to team building in the company, the higher is mutual trust and cooperation	Attitude for team cooperation	Cooperation within the team helps employees realise complicated daily tasks
				Cooperation can lead to a breakthrough in thinking
			Intensity of direct contact between employees	Employees contact each other about problems concerning the development of products and services within the enterprise permanently and systematically
				Special emphasis is put on the development of interpersonal contacts within the enterprise
		H2_2: The more frequent are direct contacts between employees, the higher is the mutual trust and cooperation		Informal rules and norms of operations dominate in the enterprise
			Atmosphere in employee relationships	Lack of involvement vs. involvement
				Lack of trust vs. trust
		H2_3: The better is the work atmosphere in the company, the higher is mutual trust and cooperation		Stagnation vs. orientation on the development
				Secrecy vs. openness

Factor	Basic hypothesis	Specific hypothesis	Variables	Options
communication processes within the company	**H3**: The more efficient are communication processes in the company, the higher is the IC ability to gain a competitive advantage in the market	**H3_1**: The more system of information fosters spontaneous communication, the higher is the quality of communication processes between employees within the company	Conditionality of communication processes	Informal flow of information and knowledge exists in the organisation
				Employees are encouraged to develop the dialogue and discussion within the company
				Flow of information and knowledge between employees is intense and easy
				Image of the firm in the employees' eyes is formed by intense communication via dedicated channels
		H3_2: The more differentiated are the means of communication, the higher is the quality of communication processes between employees within the company		Channels of communication connected with information passing are used intensely
				Channels of direct communications and relationships are used intensely
				Different ways of communication which boost knowledge and enable reaching numbers of people are used widely within the enterprise
public image and reputation in the market	**H4**: The higher is the care for the public image and reputation of the company, the higher is the IC ability to gain a competitive advantage in the market	**H4_1**: The more the marketing communication system fosters the building of positive experiences between clients and the organisation, the higher is the care for the public image and reputation of the company	Building a positive client experience	Aspiration of the enterprise for getting the highest quality of offered products and services is visible
				Systematic growth of the cooperation with clients (or potential clients) is practised to satisfy their wants and requirements
				Aspiration of the enterprise for getting the highest quality of client service is visible
			Diversified product offer	Efforts of the enterprise aimed at a developing product and service offer most often concentrate on building innovative products and services
		H4_2: The more diversified is the product offer, the higher is the care for the public image and reputations of the company		Enterprise is perfect in the creation of new kinds of products and services
				Strategy realised by the enterprise relies on the implementation of numerous and dynamic changes in the product-service offer to give clients the best product

Source: (Jurczak, 2012).

Partial indices $\chi 2/dof$ corresponding to each factor of the model are less than 2 ($\chi 2/dof < 2$), which is commonly assumed as a good fitting of the model. Partial indexes of the RMSEA are in the range 0.00-0.05, while the critical value for the quality of the model is 0.1. Moreover, even such sophisticated and challenging indices as GFI and AGFI in the case of subsequent factors exceed the 0.9 value, which confirms the good quality of the model components. Basic statistics of the fitting quality in the case of a complete model are equal to 0.711 for the $\chi 2/dof$ index and 0.001 for the RMSEA index. More advanced GFI and AGFI indices do not exceed the recommended value of 0.9 in this case. They are equal to 0.876 and 0.857, respectively. Lower than expected values of GFI and AGFI fitting indexes do not immediately attest to the poor quality of the model. Calculated values of fitting indexes, in the case of a complex model, usually are low, and in this case, the result can be treated as a rather satisfying fitting. Such a situation is typical in the case of complex model analysis, and it suggests the need for further improvements within the proposed model. Because of the relatively high fitting of compositional factors, the model improvement should be realised mainly by considering an alternate factor that may improve the fitting index of the model as a whole.

A closer look at the model and factor loadings points out the importance of the mutual trust and cooperation factor. Factor loading equal to 0.9 indicates the best matching with measured data and sug-

Tab. 6. Partial fitting statistics for each component of the IC model in getting a competitive advantage

Measure	Description	Value	Factor
χ2/ss	***chi square / degrees of freedom*** measures the fitting accuracy.	0.848	Knowledge and skills of employees
	χ2< 2 — the model is very well attuned	1.059	Mutual trust and cooperation
	to the data.2 < χ2/dof <5 — the model is acceptable.	0.964	Communication processes within the company
	On the grounds of *chi-square* value and high probability, the initial hypothesis about good matching of the model can't be rejected.	1.355	Public image and reputation in the market
RMSEA	***Root mean square error of approximation*** (RMSEA) measures the error resulting in the discrepancy between the model and population covariance matrix.	0.000	Knowledge and skills of employees
		0.021	Mutual trust and cooperation
	RMSEA < 0.05 — the model is well matched.	0.000	Communication processes within the company
	0.05 < RMSEA < 0.08 — the model is acceptable.		
	RMSEA > 0.1 — the model definitively has to be rejected.	0.039	Public image and reputation in the market
GFI	***Goodness of fit index*** (GFI) measures the fit between the hypothesised model and the observed covariance matrix. Measures range between 0 and 1.	0.975	Knowledge and skills of employees
		0.973	Mutual trust and cooperation
	GFI > 0.9 — the model is acceptable.	0.983	Communication processes within the company
	GFI = 1 — the perfect matching.	0.983	Public image and reputation in the market
	GFI < 0.9 — the model needs improvements.		
AGFI	***Adjusted goodness of fit index*** (AGFI) corrects the GFI, which is affected by the number of indicators of each latent variable. Measures range between 0 and 1.	0.957	Knowledge and skills of employees
		0.949	Mutual trust and cooperation
	AGFI > 0.9 — the model is acceptable.	0.964	Communication processes within the company
	AGFI < 0.9 — the model needs improvements.	0.956	Public image and reputation in the market

Source: (Jurczak, 2012).

gests its importance within the model of the IC ability to gain competitive advantage. Another common factor with a high value of factor loading is the level of employee knowledge and skills. This factor also constitutes an important contribution to the IC ability. The remaining factors with lower values of factor loadings (which are still significant, i.e. 0.73 and 0.70) constitute supplementary factors of the IC ability to gain competitive advantage.

4. Discussion

Generally, factor analysis as a research tool in business management is rare as its application involves some difficulties. On the one hand, the key points are rather limited awareness of the FA potential and complicated and challenging methodology (the sample size and result interpretation) on the other, extensive experience is required to perform

factor analysis and avoid misinterpretation of revealed factors. Presented FA studies, both exploratory in the case of market success and confirmatory in the case of intellectual capital, illustrate successful applications within business management. The presented studies show how to reduce a large number of initial variables and replace them with several common factors without losing the quality of the description. The complementary use of factor analysis techniques, namely, the exploratory FA first and the confirmatory FA next, allow for model creation and its verification by comparison with experimental data. As presented above, FA allows revealing several factors and attributing its general meaning to such an intangible phenomenon as market value or competitive advantage of the company. It is possible to evaluate the influence of the underlying factors in the creation process of added value, competitive advantage, or just to evaluate benefits related to company assets of any kind. Factor analysis results indicate that exploratory and confirmatory analyses allow studying complex problems within the management of company competitiveness with high accuracy and reliability. Its use may lead to the formulation of more accurate theoretical models, well-tailored to given measurements, and give more accurate tools to predict the future. The use of FA positively affects the quality of theoretical models within business management. From this point of view, FA is applied to define company standards within complex problems of business management. Nevertheless, FA procedures are rather complicated, so extensive experience and caution are required along with sophisticated software to perform the time-consuming calculation.

Conclusion

Despite the enormous potential, there are still many issues related to the FA application and barriers to its popularisation as a common research technique within management sciences. The first barrier is the complicated nature of FA, but maybe a more important issue is the lack of awareness about the factor analysis and its potential within management practice. The literature dealing with the problem lacks reports which may introduce the inexperienced reader to the use of FA in company management. Its application needs a good understanding of FA principles, assumptions, threats and theoretical knowledge supported by experience to give a correct meaning to the revealed structure of the problem. Therefore FA, much like other statistical methods, is also based on researcher competences and makes the procedure slightly arbitrary. E.g. the choice of factors is completely subjective and based on personal experience. The same concerns interpretation of the factor meaning. It requires knowledge and can hardly be formulated in any rigorous form. Fortunately, the application of different criteria to verify and compare results allows drawing general conclusions of the analysis. Summing up, experience and knowledge in the field of studied cases remain the most important factor for the successful application of FA in management sciences.

Literature

Brown, T. A. (2006). *Confirmatory Factor Analysis for Applied Research*. New York – London: The Guilford Press.

Cabuñas, J. T., & Silva, D. L. (2019). Exploratory Factor-Item Analytic Approach for Construction Project Cost Overrun using Oblique Promax Rotation for Predictors Determination. *International Journal of Innovative Technology and Exploring Engineering*, *8*(6s3), 47-54.

Chidambaram, V., Ramachandran, A., & Thevar, S. S. (2013). A study on efficacy of induction training programme in Indian railways using factor analysis. *Business: Theory and Practice*, *14*(2), 140-146. doi: 10.3846/btp.2013.15

Cortés Sánchez, J. D., & Grueso Hinestroza, M. P. (2017). Factor analysis evaluation of Schein's career orientations inventory in Colombia. *Business: Theory and Practice*, *18*, 186-196. doi: 10.3846/btp.2017.020

Czopek, A. (2013). Analiza porównawcza efektywności metod redukcji zmiennych - analiza składowych głównych i analiza czynnikowa [Comparative Analysis of Effectiveness of the Methods for Reduction of Variables - Principal Component Analysis and Factor Analysis]. *Studia Ekonomiczne*, *13*, 7-23.

Frątczak, E. (2009). *Wielowymiarowa analiza statystyczna. Teoria, przykłady, zastosowań z systemem SAS [Multivariate Statistical Analysis. Theory and Application with SAS]*. Warszawa, Poland: Wydawnictwo SGH.

Górniak, J., & Wachnicki, J. (2010). *Pierwsze kroki w analizie danych [The first steps towards data analysis]*. Kraków, Poland: SPSS Polska.

Hawrysz, L. (2019). *Wpływ zdolności dynamicznych na funkcjonowanie e-administracji [Effect of dynamic abilities on the e-administration operation]*. Radom, Poland: Instytut Technologii Eksploatacji - PIB w Radomiu.

Jaskóła, K. (2014). *Geneza sukcesu. Dynamiczne zarządzanie korporacjami przemysłowymi [Genesis of the success. Dynamic management of industry corporations]*. Radom, Poland: Instytut Technologii Eksploatacji - PIB w Radomiu.

Jurczak, J. (2012). *Czynniki kształtujące kapitał intelektu-*

alny w osiąganiu przewagi konkurencyjnej [Factors related to the intellectual capital of the company and their role in the competitive advantage]. PhD thesis. Wrocław, Poland: Politechnika Wrocławska.

Jurczak, J. (2015). Badanie kapitału intelektualnego metodą analizy czynnikowej [Factor analysis study of the intellectual capital]. *Przedsiębiorstwo Przyszłości*, *3*(24), 48-58.

Łobos, K., & Szewczyk, M. (2011). Wartość jako uniwersalna miara sukcesu w zarządzaniu przedsiębiorstwem [Value as universal measure of success in enterprise's management]. *Management Sciences*, *8*, 379-388.

Ludwikowska, K. (2021). The mediating role of employee-oriented human resource policy in the relationship between strategic human resource management and organisational performance. *Forum Scientiae Oeconomia*, *9*(2), 131-150. doi: 10.23762/FSO_VOL9_NO2_7

Maciejewski, G. (2011). Wykorzystanie analizy czynnikowej w badaniach konsumenckiego ryzyka [The use of factor analysis in consumer risk research]. *Prace naukowe Uniwersytetu Ekonomicznego we Wrocławiu*, *236*, 192-202.

Mulaik, S. A. (1987). A Brief History of the Philosophical Foundations of Exploratory Factor Analysis. *Multivariate Behavioral Research*, *22*(3), 267-305.

Nawojczyk, M. (2002). *Przewodnik po statystyce dla socjologów [Statistics guide for sociologists]*. Kraków, Poland: SPSS Polska.

Pearson, K. (1901). On Lines and Planes of Closest Fit to Systems of Points in Space. *Philosophical Magazine, 2*, 559.

Renault, B. Y., Agumba, J. N., & Ansary, N. (2018). An exploratory factor analysis of risk management practices: A study among small and medium contractors in Gauteng. *Acta Structilia*, *25*(1), 1-39.

Sagan, A. (2003). *Model pomiarowy satysfakcji i lojalności [Metrological model of satisfaction and loyalty]*. StatSoft Polska.

Spearman, C. (1904). General intelligence, objectively determined and measured. *American Journal of Psychology*, *15*, 201-293.

Staniec, I. (2012). Analiza czynnikowa w identyfikacji obszarów determinujących doskonalenie systemów zarządzania w polskich organizacjach [Factor analysis in the identification of areas that determine the improvement of management systems in Polish organizations]. *Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu*, *242*, 406-415.

Sztemberg-Lewandowska, M. (2008). *Analiza czynnikowa w badaniach marketingowych [Factor analysis in marketing research]*. Wrocław, Poland: Wydawnictwo Uniwersytetu Ekonomicznego we Wrocławiu.

Thurstone, L. L. (1933). *A Simplified Multiple-factor Method.* Chicago: University of Chicago Press.

Thurstone, L. L. (1947). *Multiple factor analysis.* Chicago: University of Chicago Press.

Vincent, D. F. (1953). The Origin and Development of Factor Analysis. *Journal of the Royal Statistical Society. Series C (Applied Statistics), 2*(2), 107-117.

Warter, L., & Warter, I. (2017). Unmasking post-merger challenges: synergy effects achieved by the integration of different areas. *Forum Scientiae Oeconomia*, *5*(2), 69-85. doi: 10.23762/fso_vol5no2_17_6

Wipulanusat, W., Panuwatwanich, K., & Stewart, R. A. (2017). Exploring leadership styles for innovation: an exploratory factor analysis. *Engineering Management in Production and Services*, *9*(1), 7-17.

Zgrzywa-Ziemak, A., & Kamiński, R. (2009). *Rozwój zdolności uczenia się przedsiębiorstwa [Development of business learning ability]*. Warszawa, Poland: Difin.

sciendo

ISMSME International Society for Manufacturing, Service and Management Engineering

received: 1 April 2021
accepted: 31 August 2021

pages: 37-49

Improvement of production process capability — a case study of two furniture companies

Andrea Sujová Lubica Simanová

ABSTRACT
The article aims to assess the improvement of the process capability by implementing the Six Sigma methodology in furniture enterprises with different levels of the quality management system (QMS) and ownership. The implementation of the Six Sigma methodology according to the DMAIC steps, also analysis, evaluation, and comparison of the implementation results were performed to improve the process performance. The implementation of the Six Sigma methodology was carried out in an international enterprise with foreign capital and a certified Quality Management System (QMS) and in a domestic enterprise with purely domestic capital without an established Quality Management System. The implementation results confirmed the positive development in the key indicators of critical processes, namely, in the reduction of DPMO, the increase of efficiency and the level of Sigma Process, and the values of process capability indices. The positive effects were more pronounced in the international enterprise compared to the domestic. The application of the Six Sigma methodology brings better results in manufacturing companies with international management skills and implemented certified QMS. These two aspects can be key success factors by managing and improving process capability. The practical contribution of the paper can be seen in the proposal of suitable methods and tools by implementing Six Sigma conception in furniture manufacturing regardless of the ownership or level of quality management systems.

KEY WORDS
process performance, quality, process capability indices, Six Sigma methodology, furniture enterprises, domestic capital, foreign capital

10.2478/emj-2021-0020

Andrea Sujová

Technical University in Zvolen, Slovakia
ORCID 0000-0002-1447-8641

Corresponding author:
e-mail: sujova@tuzvo.sk

Lubica Simanová

Technical University in Zvolen, Slovakia
ORCID 0000-0003-0374-2926

Introduction

Changes in the economic and political situation in Slovakia reflect not only in the ownership of enterprises but also, subsequently, in their management through performance and process quality. Due to the increasing pressure on the quality of products and services, enterprises are moving from traditional quality management methods to new approaches. A specific study of the application of the Six Sigma methodology to ensure and increase the quality of

Sujova, A., & Simanova, L. (2021). Improvement of production process capability — a case study of two furniture companies. *Engineering Management in Production and Services, 13*(3), 37-49. doi: 10.2478/emj-2021-0020

selected production processes in furniture enterprises with different ownership and degree of a quality management system is an example of differences in process management, which aims to improve quality and performance of furniture enterprises in the wood processing industry. The Slovak economy is highly dependent on foreign capital, which increases the productivity of the economy. In Slovakia, up to 40 % of value added is produced by companies with foreign capital, bringing new trends in business management. In the Slovak Republic, 9591 companies are controlled by entrepreneurs from the neighbouring Czech Republic with their own share of over EUR 2.366 billion. This number of companies is the largest in Slovakia. In terms of capital controlled in Slovakia by foreign owners, the Netherlands leads with a share amounting to more than EUR 5.174 billion (www.etrend.sk).

As for the wood processing industry, the largest companies in Slovakia include Ikea Industry Slovakia, Swedwood Slovakia, Mondi SCP, Essity Slovakia, s.r.o., Metsa Tissue Slovakia, Bukocel, Kronospan, SHP Harmanec, Ekoltech, Rettenmeier Tatra Timber, Doka drevo, Decodom, and Bukóza Export-Import (www.etrend.sk). According to statistical data and own research results, 51 % of furniture companies in Slovakia are domestically owned.

Following the results of the research on a sample of 188 enterprises, the ownership of Slovak wood processing enterprises is shown in Fig. 1. Enterprises of the wood processing industry are divided into wood, furniture and pulp and paper categories.

In quality assurance and performance improvement of processes, an important role is given to sound decisions based on a situation analysis using appropriate tools and methods of operational management and quality improvement. The Six Sigma methodology is used to ensure and improve the quality of processes, increase the capability of business processes, and focus on the customer. Its implementation resulted in substantial cost savings, especially in the engineering, automotive and electrical engineering industries and services. Based on STN EN ISO 9001:2015, the quality management system (QMS) is the starting point for the use of concepts, methods, tools, and techniques in companies with different specialisations, including furniture enterprises. If systematic methods of process management, statistical analyses, data from measurements of operational performance and subsequent process improvement are used, the occurrence of zero defects is also assumed.

According to the available information, the Six Sigma methodology is not used in the furniture industry of the Slovak Republic to ensure and continuously improve the quality of processes. Based on results from the application of the Six Sigma methodology in other industries, there is space for searching its possible effects under specific conditions of furniture manufacturing. Moreover, it is worthwhile to find out if implemented QMS and international management in a company result in better effects.

This paper aims to present and compare the impacts of using the Six Sigma methodology on the performance of processes in furniture enterprises with different types of ownership and levels of a quality management system. Process performance analysis in terms of process capability forms the basis for selecting the appropriate combination of methods and tools within the Six Sigma methodology. Comparing the level of process capability before and after implementing selected Six Sigma methods made it possible to identify the impacts of this concept on the performance of processes in two types of companies, international and domestic, operating at the national level.

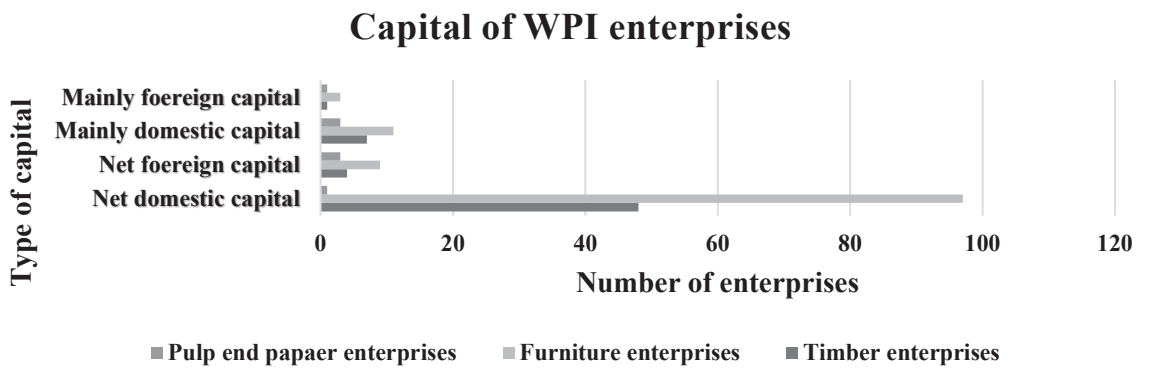

Fig. 1. Capital of WPI enterprises

Source: elaborated by the author.

1. Literature review

Motorola developed Six Sigma to improve product quality, where high component counts often resulted in a correspondingly high probability of defective final products (Arnheiter & Malexeff, 2005). Six Sigma improves productivity through process variation reduction.

Six Sigma is defined as a business strategy that increases and reduces the factors of defects and failures, increases productivity, reduces cycle time and productions costs. Six Sigma is a statistical method used for reducing variations in any process, as Näslund (2008) and Chakravorty et al. (2012) suggest. Drohomeretski et al. (2013), Shah et al. (2008), Manville et al. (2012), Lee and Wei (2009), and Näslund (2008) subjoin reducing costs in manufacturing and services, making savings in the bottom line, increasing customer satisfaction measuring defects, improving product quality (Pabedinskaitė & Vitkauskas, 2009), and reducing defects to 3.4 parts per millions of opportunities in the organisation. Six Sigma is a methodology that highlights the variation in the manufacturing process and helps to reduce them through their statistical tools and techniques (Vinodh & Swarnakar, 2015). Six Sigma is a data-driven process improvement methodology used to achieve stable and predictable process results by reducing process variations and defects (Laureani & Antony, 2017). Six Sigma statistical methods provide a structured approach for identifying the root causes of production defects (Schroeder et al., 2008). According to Kadri (2013), Six Sigma processes show a proven approach for businesses and organisations to improve their performance, and that sustainability programmes need this operational approach and discipline. Six Sigma helps a business leader to design a sustainable programme for value creation. Sachin and Dileeplal (2017), Kumar et al. (2011), and Chandrea et al. (2014) state that Six Sigma methods can be implemented by two different strategies, i.e., Define, Measure, Analyse, Implement, Control (DMAIC) and Define, Measure, Analyse, Define, Validate (DMADV). DMADV deals with new product development, while DMAIC is used to bring improvements in existing products or processes. Steps of the DMAIC procedure endeavour to adopt a smarter way of doing things so as to minimise the occurrence of errors. It emphasises doing things right the first time, rather than spending effort on correcting errors (Okpala, 2012).

Process capability refers to the evaluation of how well a process meets specifications or the ability of the process to produce parts that conform to engineering specifications. Process control refers to the evaluation of process stability over time or the ability of the process to maintain a state of good statistical control. According to Yerriswamy et al. (2014), process capability can be evaluated through the computations of various process capability ratios and indices.

According to several researchers, such as Wang et al. (2017), Gong et al. (2017) and Chen et al. (2019), the process capability index PCI can be used as a Six Sigma evaluation tool and successfully applied in various industries. Process capability indices are intended to provide a single number assessment of the ability of a process to meet specification limits on quality characteristics of interest. Thus, it identifies the opportunities for improving quality and productivity. Cp and Cpk capability indices allow an assessment of the process's critical capability in terms of compliance with a set or expected limits and average value according to Al-Agha et al. (2015) and Simanová (2015). Chen et al. (2003), Ray and Das (2011), and Gejdoš (2006, 2014) consider the Cp and Cpk indices to be the most used basic indicators of competence in the manufacturing industry.

The research results on the use of the Six Sigma methodology, which is currently known worldwide, show the successes and failures of implementation. Currently, many companies in Europe and America show economic benefits after implementing the Six Sigma concept. Motorola is widely believed to be the first company to announce success in implementing Six Sigma. While Japanese companies experienced benefits earlier, American companies were the first to disseminate their results, leading to rapid takeovers by other companies (Montgomery, 2016; Madhani, 2017).

Following the successful implementation of Six Sigma, other industries have followed, such as Toyota, IBM, AlliedSignal, General Electric, Xerox, Kodak, Ford, General Motors, BMW, Hilti, Shell, Honeywell, Chrysler etc. (Khumar, 2006). Other companies that have shown success in implementing Six Sigma are listed by Kwak and Anbari (2006). The Six Sigma methodology is also used by some Slovak companies, e.g., Telecom, U.S. Steel, Kooperatíva insurance company, Jungheinrich, VST Oceľ, Kosice, Nemak Žiar nad Hronom, ZTS Strojárne Námestovo, Prima banka (www.fbe.sk).

Project success is determined by such factors as the connection of Six Sigma projects to the business goals of the enterprise, key performance indicators, quality costs, involvement of senior management with sufficient influence, security of resources, access to reliable data, project completion within a specified time limit, use of statistical tools and information technology, human resources. According to Kwak and Anbari (2006), Vest and Gamm (2009), and Chow and Moseley (2017), these factors are local, may not apply to all companies and their implementation without adaptation to the environment may be another factor in failure. Similarly, Antony et al. (2007) and Raman et al. (2017) mainly mention the economic benefits for companies derived from the Six Sigma implementation. Garcia-Alcaraz et al. (2017), for example, performed an analysis to combine human factors with operational benefits, such as labour productivity, product rejection levels, and client complaints, where economic benefits were also achieved. It can be stated that the implementation of the Six Sigma concept is strongly influenced by the level of human resources.

The failures and causes of a Six Sigma failure have been reported in the work of several authors. The reasons for failure include inadequate understanding of the concept and scope of the methodology, insufficient education and training, poor management strategies and a lack of supporting organisational structures (Chakravorty 2009; Nourelfath et al., 2016). Kumar et al. (2014) found that the absence of activities related to the lead manager, as well as the subsequent misunderstanding of the Six Sigma project by other team members, was the main cause of the failure. Further reports and analyses regarding critical success factors for Six Sigma are offered by Mustafa and Jamaluddin (2017), Ribeiro de Jesus et al. (2016), Alhuraish et al. (2017), Marzagão and Carvalho (2016), Psomas (2016), and Lande et al. (2016).

2. Research methods

The input information for the research, the determination of its objectives, and the implementation process were obtained by summarising the findings from available publications, mostly by foreign authors, listed in Section 1. The research methodology is based on general methodology by primary research, and it was adjusted to the combination of primary quantitative research and the applied research by case studies. The framework of our research is shown in Fig. 2.

Primary research in furniture manufacturing enterprises was conducted to determine the extent of the use of the Six Sigma methodology, and concepts, methods and tools for managing the performance of business processes and improving their quality. Relevant data were obtained through an online research questionnaire. The questionnaire included four general questions, such as enterprise size by an average number of employees, focus, business ownership, return on equity, and eight questions focusing on areas such as process types, performance management, process capability, quality management system certification, as well as the use of selected concepts and methods of process performance management.

A total of 479 furniture enterprises were contacted, and 188 questionnaires were returned, representing 39.25 % of the total number of enterprises

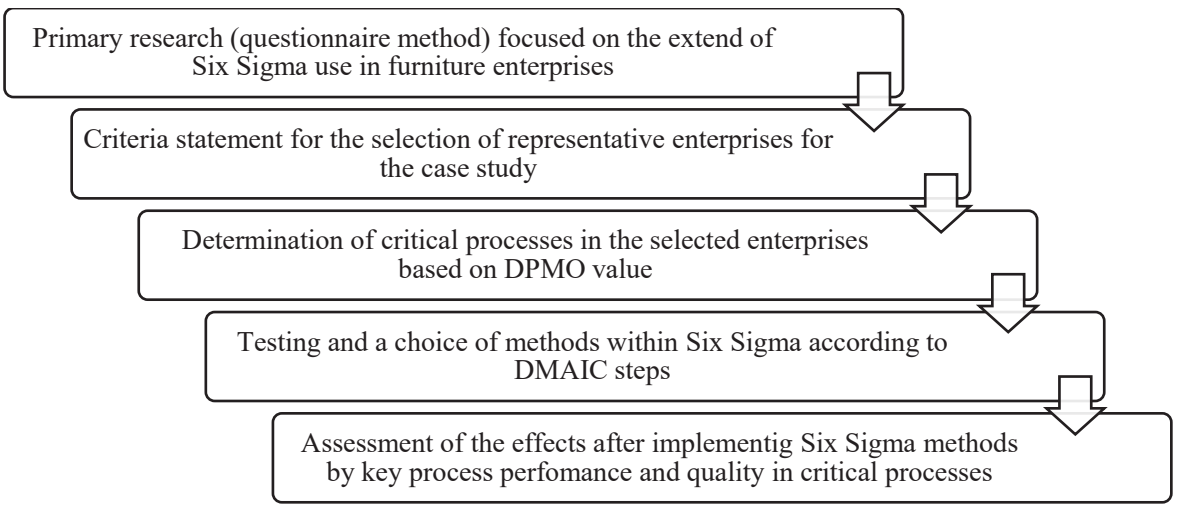

Fig. 2. Research framework

Tab. 1. Overview of factors of selected enterprises for the implementation of Six Sigma

ENTERPRISE	International	Domestic
TYPE OF CAPITAL	Purely foreign	Purely domestic
MARKET ACTIVITY	Longer than 10 years	Longer than 10 years
FOCUS OF THE MAIN ACTIVITY	Furniture production	Furniture production
CERTIFICATION QMS	ISO 9001, ISO 14001, OHSAS 18001	None

contacted. According to the calculation of the sample size using the equation of the Raosoft application, this is a statistically significant sample at a 92 % confidence level and a 5 % margin of error. The results were processed in the Statistic program, and descriptive statistics modules were used.

Based on the results of the primary research, the criteria for the selection of representative enterprises were set out in Table 1 for the implementation of the second part of the research focused on the implementation of the Six Sigma concept in selected enterprises.

Relevant data for the calculation of critical indicators of furniture production processes were obtained from the databases of the surveyed enterprises and by own measurement of process characteristics.

A critical process and a specific process problem were identified by the defect analysis in the process. Defects were divided into material and technological. Calculations of the DPMO value were used as well as the process efficiency as total output revenue and a level of Six Sigma. DPMO (Defects per Million Opportunities) denominates the number of defects that occur per one million opportunities at the development or manufacturing of a product and can be calculated by the formula 1.

Modules of Descriptive statistics and Industrial statistics and Sigma process analysis was used for the calculations (Statistica CZ).

When implementing the Six Sigma methodology in enterprises with different types of ownership and QMS certification level, several methods were selected in the individual phases of DMAIC as described below.

The Define Phase was characterised by detecting VoC (Voice of Customers) and specific customer requirements using the CTQ (Critical to Quality) method. The Quality Function Deployment (QFD) method displays the transformation of customer requirements into a product. Non-conformance record tables and Six Sigma industry statistics modules for calculating and comparing Defects per Million Opportunities (DPMO) indicators, process efficiency levels, and Sigma process levels identify critical processes. The Pareto diagram determines the priority cause affecting process performance. The project charter is used as a plan to address performance and process improvement.

In the Measure Phase, key parameters of the critical process were defined using the measurement plan according to Pande et al. (2002). Due to the possibility of comparing the performance of critical processes of individual enterprises before corrective measures and after their implementation, the calculations of the capability indices C_p and C_{pk} were chosen. These were performed through industrial statistics and Sigma process analysis, graphical representation via histograms and control charts, and provided a suitable platform for the final comparison of results.

The essence of the Analyse Phase consisted of analyses of discrepancies, DPMO values, values of the efficiency level of furniture production processes, Sigma process levels, measurement results and problem identification, as well as Ishikawa diagram for decomposition of first degree causes into second and third-degree causes, affinity diagram for finding causes in a broader context. An analysis of possible errors and their consequences used FMEA (Failure Mode and Effect Analysis) and the Brainstorming method as a highly operative method based on the principle of collective discussion.

The Improve Phase is characterised by a response plan with proposals for corrective measures to eliminate the causes of problems affecting the performance of critical processes. The verification of corrective action results was considered an integral part of this DMAIC step and was implemented through methods of analysis and synthesis, industry statistics & Sigma process analysis, statistical modules for process analysis, histograms and control charts.

In the Control Phase, in addition to primary information from non-compliance records, DPMO indicators, process efficiency levels, Sigma levels, an

$$DPMO = \frac{number\ of\ defect\ products}{\text{total number of products} * \text{number of opportunities per defect}} * 10^6 \qquad (1)$$

affinity diagram were selected to identify logical and causal relationships in solving quality and performance problems from a broader perspective. For monitoring and comparing critical process indicators, the intention was to use the methods of the previous DMAIC steps, such as process capability indices (C_p, C_{pk}), VOC, CTQ, QFD, methods and tools, such as the affinity diagram, Ishikawa diagram and discrepancy records tables.

3. Research results

The primary quantitative research was focused on finding out the use of concepts, methods and tools in performance management and quality management in furniture enterprises. Fig. 3 shows an overview of selected concepts, methods and tools used to increase performance and improve the quality of processes in Slovak furniture enterprises, including two representative enterprises chosen for our case study.

Out of 188 furniture enterprises, most (38.30 %) enterprises used the Brainstorming method. In contrast, only 2.13 % of enterprises used the Six Sigma methodology, and 3.19 % used the Lean Six Sigma method. The analysis showed that 15.43 % – 22.24 % of enterprises used concepts and methods, such as process controlling, TQM and Kaizen. Less than 11.00 % of enterprises used individual concepts, methods and tools, such as Kanban, Poka-Yoke, Method 5S, traditional and new quality management methods, process capability indices and Statistical process control (SPC). Some (11.17 %) furniture enterprises did not use any concepts, methods and tools. The above research results show reserves in the furniture industry for the use of modern concepts and methods of performance and quality management. These conclusions confirmed the intention of the author to focus on comparing the implementation of the Six Sigma methodology for ensuring and increasing the quality of production processes in furniture enterprises with different degrees of a quality management system and with different types of ownership.

When selecting enterprises to implement the Six Sigma methodology, the research focused on the factors listed in Table 1: different types of capital and certification QMS, the same focus and length of market activities.

An enterprise with foreign capital was selected to implement an integrated management system having precisely defined procedures, guidelines and standards with described responsibilities, the frequency for ensuring quality control of input materials, work-in-progress and finished products, and detecting quality deviations. Processes were defined, and a low-level structure of processes was created, the connections between processes in the enterprise documentation were monitored, the quality of processes was monitored through the evaluation of the number of discrepancies and the costs of discrepancies. The enterprise with net domestic capital only had a manual for the description of processes and a classical technological procedure to produce furniture. From the quality control viewpoint, it had no developed quality

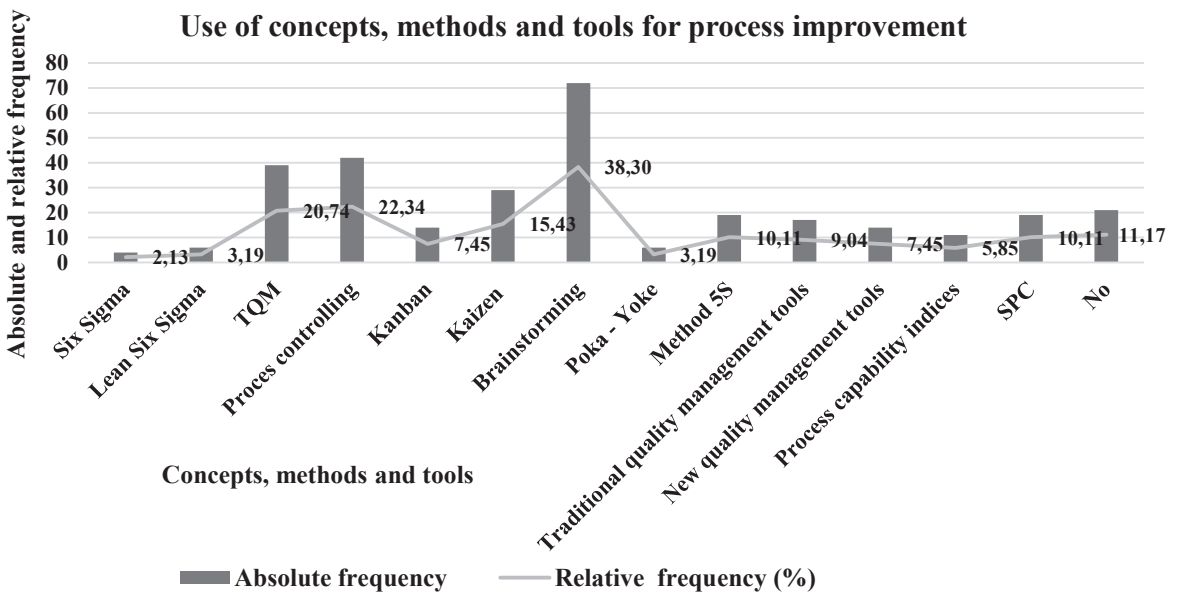

Fig. 3. Use of concepts, methods and tools for process improvement

management system. The enterprise had a high-level structure of processes, did not use methods for process management or indicators to measure process performance.

The implementation of the Six Sigma methodology started with the analysis disagreement of furniture production processes in two different enterprises from the viewpoint of ownership and QMS certification. Calculations of the DPMO values, efficiency levels and Sigma levels of furniture parts production processes were used for the purpose of comparing the results of process outputs and determining the critical process.

In the enterprise with foreign capital and with a certified QMS, the processes of formatting, glueing side surfaces, pressing, drilling holes, surface treatment, joining and handling were considered. The pressing was determined as the critical process due to the lowest process capability (the lowest value of the Six Sigma level). To determine the capability of the pressing process before and after the implementation of corrective measures to improve the efficiency and quality of the process, the adhesive deposits were measured in g/m2.

In the enterprise with domestic capital and without a certified QMS, the processes of formatting, pressing, glueing of side surfaces, grinding, and surface treatment were evaluated. Drilling was detected as a critical process due to the lowest value of Six Sigma. To determine the capability of the grinding process before and after corrective measures to improve the performance and quality of the process, the thicknesses of the furniture parts were measured (in mm).

The basic characteristics of critical processes in both enterprises were measured over a period of one month and provided a database of basic data for the calculation of C_p and C_{pk} indices, their comparison within the enterprise, as well as between selected enterprises.

The comb shape of the histograms in Figs. 4 and 5 indicates that the variability of both processes is high and is not caused by natural variability in the process. The values of the capability indices are low in both processes. In the pressing process, the total coefficient C_p has a value of 0.42 and the total coefficient C_{pk} = 0.36. In the grinding process, C_p is 0.59 and C_{pk} is 0.48. The values of both indices in the pressing and grinding processes are less than one; therefore, based on the summary results, the pressing and grinding processes are not capable. Furthermore, the indices $C_p > C_{pk}$, which means that the processes are not cantered in the middle of the tolerance interval and react to the deviation of the actual mean value of the process μ from the centre of the tolerance interval. Based on the above facts, processes contain definable, systematic causes. The comparison of the capability of processes through capability indices before measures showed that the indices were a suitable basis for comparison and that the capability of critical processes at this stage was not affected by the type of capital or QMS certification level. A higher priority was given to the comparison of capability indices after the implementation of corrective measures to improve the performance and quality of processes.

The selection of methods and tools for the implementation of the Six Sigma methodology was carried out, aiming to coach individual team members who participated in the project in both companies without special training and increased training costs. The concepts, methods and tools used according to the DMAIC steps for international and domestic enterprises, considering their specifics, are listed in Table 2.

The implementation of concepts, methods and tools within the Six Sigma methodology and according to the DMAIC steps involved outlining essential

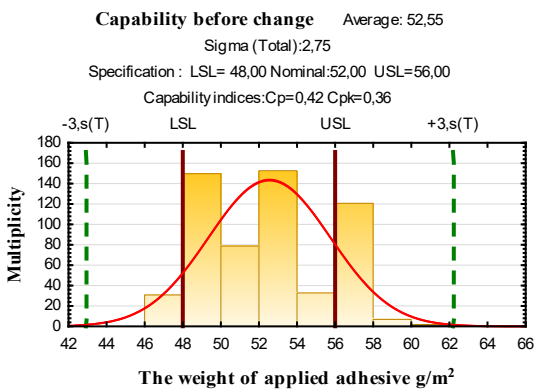

Fig. 4. Capability of the pressing process before changing

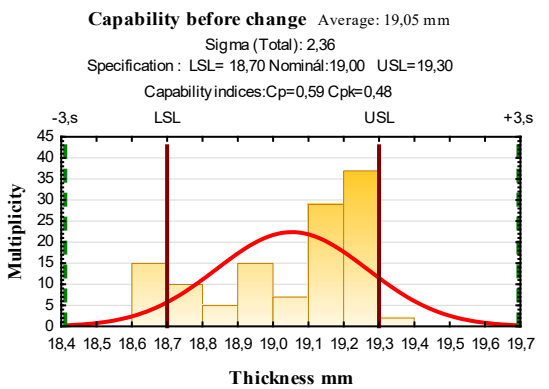

Fig. 5. Capability of the grinding process before changing

Tab. 2. Description of concepts, methods and tools for the implementation of Six Sigma in furniture enterprises with different types of ownership and certified QMS

Concepts, methods and tools	Description
Tables for recording disagreements	Excel is a suitable tool for creating tables for various purposes. A tool should be independent of the ownership type and the level of certification
Voice of Customers (VoC)	The VoC method is suitable for determining customer requirements regardless of the ownership type and QMS certification
Critical to quality (CTQ)	The CTQ method for determining critical quality parameters and deviations that the customer is able to accept. The use of this method is possible in enterprises with different ownership types and with different degrees of QMS certification
DPMO, efficiency level, Sigma level, line graphs, Pareto diagram, tables, STATISTICA program	Histograms to show the frequency of errors, the Pareto diagram to show the effect of the error on the process, line graphs, tables, and the STATISTICA program for calculating the values of efficiency level and the Sigma level are tools usable in both enterprises regardless of the level of the QMS implementation
DMAIC	An appropriate methodology for both enterprises, regardless of the level of QMS implementation and the ownership type
SIPOC map (Supplier, Input, Process, Output, and Customer	SIPOC map is a simple tool for mapping business processes. The pressing process in an international enterprise is characterised by a wider number of operations, line synchronisation, established standards certified by QMS; therefore, this method is more suitable for this enterprise. From the viewpoint of the furniture production process in the domestic enterprise, it will first be necessary to create process maps of existing processes
Project charter	A suitable tool for a basic description of the project, setting goals, deadlines and responsibilities for both enterprises, regardless of the ownership type and the level of certified QMS
Process diagram	The Pareto diagram identifies and prioritises problems. It is a simple and clear tool for managerial decision-making in both enterprises, regardless of the level of QMS certification and the ownership type
Measurement plan according to Pande - Neuman - Cavanah (2002)	This measurement plan is suitable for both types of enterprises with the adaptation of the individual steps of the plan to the technological conditions and the scope of production in the enterprise
Descriptive statistics. Capability indices C_p a C_{pk}, histograms	The use of the STATISTICA program for both enterprises is, from the viewpoint of the use of Six Sigma methods and tools, a necessary aid in identifying critical processes based on capability indice
Ishikawa diagram	The Ishikawa diagram, a suitable tool for decomposing the causes of disagreements, can be used in both enterprises with different types of ownership and QMS certification levels, with certain variations considering the specifics of the processes
Reaction plan	In practice, this tool is very effective and similar to a control diagram. It is suitable for a specific textual and graphical description of a process or operation with the setting of process characteristics. The reaction plan can also serve as a type of standard in the production process. Suitable for both types of enterprises
Quality Function Deployment (QFD)	The differences and sophistication in the construction of the Quality House depend on determining the importance of the requirements and the determination of the product properties in the enterprises, as well as on their technical and qualification equipment. The tool can be used in both types of enterprises with interest in the transformation of customer needs into product quality. Its use depends on the level of management, and the use of VoC and CTQ methods, which in an enterprise with domestic capital and without a certified QMS, is demanding but not impracticable
Pareto diagram	A Pareto diagram is a suitable tool for illustrating the effect of the error on process output. It is applicable in both enterprises regardless of the type of ownership and the level of certified QMS
Brainstorming	This method is very effective, creative, and usable for solving problems in various types of enterprises, regardless of the level of QMS and the ownership type
Affinity diagram	The diagram is suitable for identifying logical and causal connections. Its creation had to be adapted to the specific conditions of enterprises with different ownership types and levels of the QSM certification
Diagram of hierarchical and personnel provision of projects	A graphical method of personnel occupancy in Six Sigma projects and its synchronisation with managerial functions. It must be adapted to organisational and competence structure according to an ownership type and level of QMS
Control diagrams	The graphical method is suitable for both types of enterprises for analysis and synthesis of obtained measurement results of process characteristics, the use of industrial statistics & Sigma process analysis, and statistical modules for process analysis and creation of control diagrams

activities for increasing the performance of processes in terms of quality and recommended methods for the implementation of concepts, methods and tools within the Six Sigma methodology and according to the DMAIC steps, essential activities for increasing the performance of processes in terms of quality and recommended methods for its assurance.

The priority of the implementation of the Six Sigma concept, specifically the Improvement Phase, was to take such measures as would ensure an increase in the capability of critical pressing and grinding processes in two selected furniture enterprises. Figs. 6 and 7 show the changes in the shape of the histograms and the concentration of the basic characteristics of the critical processes between the tolerance limits of the pressing and grinding processes.

Table 3 demonstrates the comparison of key performance and quality indicators of processes, such as the DPMO of the critical processes, efficiency and Sigma process levels, Cp capability indices and Cpk critical capability indices, the number of non-conforming products, cost of non-conforming products in an international foreign capital company and a domestic company with purely domestic capital.

The knowledge from the implementation of individual concepts, methods, and tools of the Six Sigma concept according to DMAIC steps showed that in both selected enterprises with different levels of QMS certification and different ownership, the same methods could be applied to improve process performance and quality. The results shown in Table 3 demonstrate that the concepts, methods, and tools implemented within the Six Sigma methodology used to improve the quality and performance of critical furniture manufacturing processes can be considered effective and efficient in foreign and domestic enterprises. This fact was also confirmed by the verification results of the Six Sigma concept implementation according to the DMAIC steps in critical pressing and grinding processes based on comparable indicators of their performance. In an enterprise with foreign capital and certified QMS, pressing was defined as a critical process with DPMO values before the improvement amounting to 107 536.58, efficiency level value of 89.25 and Sigma level of 2.75 and with DPMO values after the improvement equal to 53 325.46, efficiency level value of 94.67 and Sigma level of 3.11. The grinding process was defined as a critical process in an enterprise with domestic capital and without a certified SMK with DPMO values before the improvement amounting to 197 629.13, efficiency levels of 80.24 and Sigma levels of 2.36, and with DPMO values after the

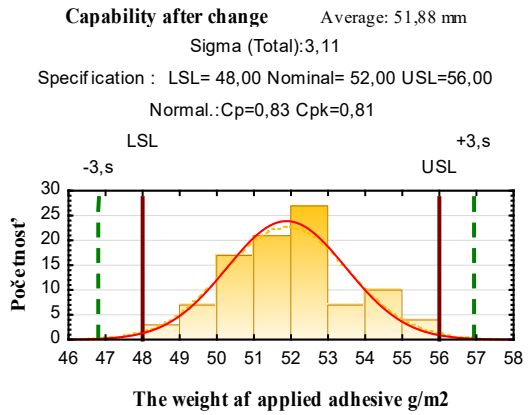

Fig. 6. Capability of the pressing process after the change

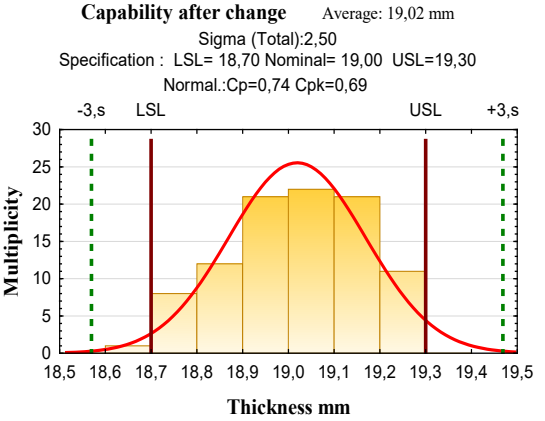

Fig. 7. Capability of the grinding process after the change

Tab. 3. Results before and after the change in two furniture manufacturing companies

Key metrics	Enterprise with foreign capital		Enterprise with domestic capital	
	Before	After	Before	After
DPMO critical process	107 536.58	53 325.46	197 629,13	134 753,36
Sigma level	**2.75**	**3.11**	2,36	2,50
Effectiveness %	89.25	94.67	80,24	84,13
Capability index C_p	**0.42**	**0.83**	**0.59**	**0.74**
Capability index C_{pk}	0.36	0.81	0.48	0.69
Non-conforming products in pcs	6 879	5 324	724	629
Cost of nonconformities € (in a month)	**37 653.25**	**29 985.75**	4 923.50	4 277.20

improvement equal to 134 753.36, efficiency levels of 84.13 and Sigma level 2.5.

4. Discussion of the results

On a specific example regarding the implementation of methods and tools, improvements were recorded in key indicators for both types of enterprises, while the DPMO value of the critical process of the enterprise with foreign capital had a higher difference (by 13.09 %) before and after the implementation, and an efficiency level (by 6.07 %). The DPMO value of the critical process of the enterprise with domestic capital saw an improvement of 5.93 % and an efficiency level of 4.85 %. Even though the values of capability indices increased by more than 50 % in the international enterprise and by more than 25 % in the domestic enterprise, which was positive, these coefficients were still less than one. The number of non-compliant products and the amount of costs were lower in the observed period of one month after the corrective measures within the Six Sigma methodology by 22.6 % in an international enterprise and by 13.12 % in a domestic enterprise. Based on the above, an enterprise with foreign capital and a certified QMS had significantly higher results than an enterprise with domestic capital and without a certified QMS. Although significant differences were found in the DPMO values, efficiency levels, and Sigma levels in the critical processes of both enterprises, the implementation of the Six Sigma concept was successful in both selected enterprises. A further inquiry into a more comprehensive understanding of this success led to the conclusion that an enterprise with certified QMS and foreign capital applied the Six Sigma concept more rationally and sophisticatedly in terms of information systems, organisational structure, corporate culture, and also in the understanding of the concept by enterprise managers of various levels and employees. Although these implementation results of the Six Sigma concept reflect positive developments, critical furniture manufacturing processes have not been fully capable and still produce non-conforming products. A visible improvement of the processes occurred in the observance of tolerance limits once reaction plans were introduced into the processes with the definition of tolerance, technological and setting intervals. Based on Inal Tamer et al. (2018), Smętkowska and Mrugalska (2018), the Six Sigma concept improves the quality and performance of processes. These observations were also confirmed by the analyses results regarding the evaluation of furniture production processes in one international and one domestic enterprise. The application of new concepts, methods, and tools to ensure improved performance and quality of processes was more easily implemented in an enterprise with foreign capital, which had a certified QMS, production standards, and an established system for measuring, controlling and analysing key process characteristics.

The application of the Six Sigma methodology is closely linked to the qualification structure of human resources at various levels of management, as well as to the qualification structure of human resources directly involved in the production process. The success of the application of the Six Sigma methodology would not have been achieved without the support of the company's management, managers, and the cooperation of technicians, operators, and equipment operators. According to Bruno (2011) and Desai et al. (2012), the application of the Six Sigma methodology also differs from the size of the enterprises. The choice of appropriate methods and tools for the Six Sigma implementation also depends on the type and specifics of a production process. Regarding the technology of furniture manufacturing and a prevailing serial or custom type of production, applicable methods and tools must be chosen. This case study tested several existing methods. However, some of them proved to be inappropriate as they did not bring the desired effect. The enterprise without a certified QMS and lower process maturity had to consider the ability and readiness of employees to perform activities of proposed methods and tools. Finally, the chosen methods and tools were applied in both enterprises where the QMS level and process maturity were different, but the desired positive effects were reached.

The methods and tools used in the implementation of the Six Sigma methodology can be recommended with their adaptation to the form of capital, size of the enterprise, capacities, hierarchical process management, the implementation degree of the quality management system, as well as the educational level of employees.

The paper contributed to the development of knowledge in the implementation of the Six Sigma model under specific conditions of furniture manufacturing. The findings confirmed positive effects and a greater improvement of process capability in the environment of a certified and standardised QMS and in an enterprise with international activities. Internationally managed enterprises have a high process management maturity, more qualified and better-educated employees. These factors create better start-

ing points by implementing modern conceptions of process management, such as the Six Sigma methodology. Foreign capital brings different corporate culture to furniture enterprises, a higher degree of quality assurance through certified quality management systems, the use of methods and tools to improve process performance. The application of methods and tools to improve the process capability in furniture production provides enterprises with the opportunity to choose appropriate methods and approaches within the DMAIC steps.

Conclusions

Aiming to improve the competitiveness of enterprises, it is important to focus on such attributes as the increase in the performance and quality of processes, the level of assurance and improvement of the quality of products and services, and the satisfaction of customer needs. The implementation and certification of the Quality Management System are currently among the prioritised business strategies, but enterprise readiness is insufficient in many respects. Based on the experience implementing Six Sigma projects in international and domestic furniture enterprises with different levels of the Quality Management System, the methodology should be implemented in furniture manufacturing processes of enterprises with different ownership types as it improves quality and increases the performance of enterprises in terms of specific indicators. However, better results have been achieved in an international enterprise, which can be attributed to several causal factors, such as a high level of corporate culture, intuitive decision-making replaced by data-based decision-making, which is associated with a consistent record of basic process characteristics, the level of technical and technological standards. Besides, the implementation involved more sophisticated technical, technological and information systems, a thoroughly reworked organisational structure with the process of escalation and problem solving, and an understanding of the Six Sigma methodology, which is promoted by top-down management and developed mainly at the middle management.

The wood processing industry, except for furniture manufacturing, has promising prospects with progress and growth of competitiveness depending on the type of ownership, the level of the established Quality Management System, and the use of new methods of performance management and process quality assurance. Enterprises with foreign capital and an established and certified quality management system have a competitive advantage. Their progress is accompanied by managing constant changes in processes depending on increasing customer requirements. Companies that do not have a quality management system in place to maintain their market position are striving to streamline process quality management, which is impossible without effective new approaches.

Based on the implementation findings, home-owned enterprises that seek to increase the efficiency and quality of their processes could be recommended to increase the level of corporate culture, focus on streamlining the organisational structure and the employee qualification structure. The successful introduction of the QMS certification and the associated technical and technological standards, information systems, more sophisticated data collection on processes and product characteristics mainly depends on the understanding of management at various levels of process management. The level of management guarantees the successful implementation of new concepts and methods for managing the performance and quality of processes.

The proposed methods and tools for implementing the Six Sigma methodology presented in this paper are suitable and applicable in conditions of furniture manufacturing. Their complexity in the application is manageable even in smaller companies without an established QMS by respecting DMAIC steps.

The positive results from the implementation of the Six Sigma concept according to the DMAIC steps are the inputs for further research in increasing the performance and quality of processes using new concepts and methods not only in the furniture industry but also in the woodworking industry as a whole. The future research will be directed to modern process improvement methods and not only process capability but also their application in the specifics of different wood handling processes. The study focusing on the effects of implementing the Lean Six Sigma methods would also contribute to experience and knowledge in the improvement of process capability.

Acknowledgements

This research was supported by KEGA No. 005TU Z-4/2020 "Economics, Management and Enterprising in Wood Industry Companies — University Text-

books with the Support of Visualization in Virtual Space".

Literature

Alhuraish, I., Robledo, C., & Kobi, A. (2017). A comparative exploration of lean manufacturing and six sigma terms of their critical success factors. *Journal of Cleaner Production*, *164*, 325-337. doi: 10.1016/j.jclepro.2017.06.146

Antony, J., Antony, F. J., Kumar, M., & Cho, B. R. (2007). Six Sigma in service organisations – Benefits, challenges and difficulties, common myths, empirical observations and success factors. *International Journal of Quality and Reliability Management, 24*(3), 294-311. doi: 10.1108/02656710710730889

Arnheiter, E. D., & Maleyeff, J. (2005). The integration of lean management and Six Sigma. *The TQM Magazine*, *17*(1), 5-18. doi: 10.1108/09544780510573020

Chakravorty, S. S. (2009). Six Sigma failures: An escalation model. *Operations Management Research*, *2*(1-4), 44-55.

Chandra, S., Doloi, B., & Bhattacharya, B. K. (2014). Implementation of six- sigma methodology for improvement of process yield by reduction of rejection in a manufacturing process. In 5th International & 26th All India Manufacturing Technology Design and Research Conference (AIMTDR 2014), IIT, Guwahati, 644-1–644-6.

Chen, K. S., Pearn, W. L., & Lin, P. C. (2003). Capability measures for processes with multiple characteristics. *Quality and Reliability Engineering International*, *19*, 101-110. doi: 10.1002/qre.513

Chen, K. S., Wang, C. H., Tan, K. H., Chiu, S. F. (2019). Developing one-sided specification six-sigma fuzzy quality index and testing model to measure the process performance of fuzzy information. *International Journal of Production Economics*, *208*, 560-565. doi: 10.1016/j.ijpe.2018.12.025

Chen, M., & Lyu, J. (2009). A Lean Six-Sigma approach to touch panel quality improvement. *Production Planning & Control*, *20*(5), 445-454. doi: 10.1080/09537280902946343

Chow, A. T., & Moseley, J. L. (2017). Comparisons of six sigma, lean, and human performance technology/ performance improvement. *Performance Improvement, 56*(1), 6-13. doi: 10.1002/pfi.21677

Desai, D. A., Antony, J., & Patel, M. B. (2012). An assessment of the critical success factors for six sigma implementation in Indian industries. *International Journal of Productivity and Performance*, *61*, 426-444. doi: 10.1108/17410401211212670

Drohomeretski, E., Gouvea da Costa, S. E., Pinheiro de Lima, E., & Rosa Garbuio, P. A. (2014). Lean, Six Sigma and Lean Six Sigma: an analysis based on operations strategy. *International Journal of Production Research*, *52*(3), 804-824. doi: 10.1080/00207543.2013.842015

FBE – For Business Excellence. https://www.fbe.sk/

García-Alcaraz, J., Avelar-Sosa, L., Latorre-Biel, J., Jiménez-Macías, E., & Alor-Hernández, G. (2017). Role of human knowledge and communication on operational benefits gained from six sigma. *Sustainability*, *9*(10), 1721. doi: 10.3390/su9101721

Gejdoš, P. (2006). Method Six Sigma – flexible system for improving business performance. *Acta Facultatis Xylologiae*, *XLWIII*(2), 103-111.

Gejdoš, P. (2014). *Building and certification of quality management systems in theory and practice.* Zvolen: Technical University.

Gong, G., Chen, J. C., & Guo, G. (2017). Enhancing tensile strength of injection moulded fibre reinforced composites using the taguchi-based six sigma approach. *International Journal of Advanced Manufacturing Technology, 91*(9-12), 3385-3393. doi: 10.1007/S00170-017-0031-9

Inal Tamer, C., Goruroglu Ozturk, O., Kibar, F., Cetiner, S., Matyar, S., Daglioglu, G., & Yaman, A. (2018). Lean six sigma methodologies improve clinical laboratory efficiency and reduce turnaround times. *Journal of Clinical Laboratory Analysis*, *32*(1), e22180. doi: 10.1002/jcla.22180

Kadri, S. (2013). Six Sigma Methodology for the Environment Sustainable Development. In L. Zongwei (Ed.), *Mechanism Design for Sustainability* (pp. 61-76). Germany: Springer.

Kumar, M., Khurshid, K. K., & Waddell, D. (2014). Status of quality management practices in manufacturing SMEs: A comparative study between Australia and the UK. *International Journal of Production Research*, *52*(21), 6482-6495. doi: 10.1080/00207543.2014.948574

Kumar, S. S., Satsangi, P. S., & Prajapati, D. R. (2011). Six sigma an excellent tool for process improvement – a case study. *International Journal of Scientific and Engineering Research, 2*(9), 1-10.

Kwak, Y. H., & Anbari, F. T. (2006). Benefits, obstacles, and future of six sigma approach. *Technovation, 26*(5), 708-715. doi: 10.1016/j.technovation.2004.10.003

Lande, M., Shrivastava, R. L., & Seth, D. (2016). Critical success factors for lean six sigma in smes (small and medium enterprises). *TQM Journal*, *28*(4), 613-635. doi: 10.1108/TQM-12-2014-0107

Laureani, A., & Antony, J. (2017). Leadership and Lean Six Sigma: a systematic literature review. *Total Quality Management & Business Excellence*, *30*(4), 1-29. doi: 10.1080/14783363.2017.1288565

Lee, L., & Wei, C. (2009). Reducing mould changing time by implementing Lean Six Sigma. *Quality and Reliability Engineering International*, *26*(4), 387-395. doi: 10.1002/qre.1069

Madhani, P. M. (2017). Six Sigma Deployment in Sales and Marketing: Enhancing Competitive Advantages. *The IUP Journal of Business Strategy*, *14*(2), 40-63.

Manville, G., Greatbanks, R., Krishnasamy, R., & Parker, D. W. (2012). Critical success factors for Lean Six Sigma programming. *International Journal of Quality & Reliability Management*, *29*(1), 7-20. doi: 10.1108/02656711211190846

Marzagão, D. S. L., & Carvalho, M. M. (2016). Critical success factors for six sigma projects. *International Jour-*

nal of Project Management, *34*(8), 1505-1518. doi: 10.1016/j.ijproman.2016.08.005

Montgomery Douglas, C. (2016). Why do lean six sigma projects sometimes fail? *Quality and Reliability Engineering International*, *32*(4), 1279. doi: 10.1002/qre.2009

Mustafa, Z., & Jamaluddin, Z. (2017). Six sigma critical success factors in manufacturing industries. *AIP Conference Proceedings*, 1-8.

Näslund, D. (2008). Lean six sigma and lean sigma: fads or real process improvement methods. *Business Process Management Journal*, *14*(3), 269-287. doi: 10.1108/14637150810876634

Neely, A., Gregory, M., & Platts, K. (2005). Performance measurement system design: A literature review and research agenda. *International Journal of Operations & Production Management*, *25*(12), 1228-1263. doi: 10.1108/01443570510633639

Nourelfath, M., Aldowaisan, T., & Hassan, J. (2016). Evaluating six sigma failure rate for inverse gaussian cycle times. *International Journal of Production Research*, *54*(20), 6092-6101. doi: 10.1080/00207543.2016.1190880

Okpala, K. E. (2012). Total Quality Management and SMPS Performance Effects in Nigeria: A Review of Six Sigma Methodology. *Asian Journal of Finance & Accounting*, *4*(2), 363-378. doi: 10.5296/ajfa.v4i2.2641

Pabedinskaitė, A., & Vitkauskas, R. (2009). Multicriteria evaluation of product quality. *Business: Theory and Practice*, *10*(3), 214-222. doi: 10.3846/1648-0627.2009.10.214-222

Pande, P. S., Neumann, P. R., & Cavanagh, R. R. (2002). *We are introducing the Six Sigma method.* Brno: TwinsCom.

Psomas, E. (2016). The underlying factorial structure and significance of the six sigma difficulties and critical success factors. *TQM Journal*, *28*(4), 530-546. doi: 10.1108/TQM-04-2015-0049

Ray, S., & Das, P. (2011). Improving machining process capability by using Six Sigma, *International Journal for Quality Research*, *5*(2), 109-122.

Ribeiro De Jesus, A., Antony, J., Lepikson, H. A., & Peixoto, A. (2016). Six sigma critical success factors in Brazilian industry. *International Journal of Quality & Reliability Management*, *33*(6), 702-723. doi: 10.1108/IJQRM-08-2014-0120

Sachin, S., & Dileeplal, J. (2017). Six sigma methodology for improving manufacturing process in a foundry industry. *International Journal of Advanced Engineering Research and Science, 4*(5), 131-136. doi: 10.22161/ijaers.4.5.21

Schroeder, R. G., Linderman, K., Liedtke, C., & Choo, A. S. (2008). Six sigma: definition and underlying theory. *Journal of Operations Management, 26*(4), 536-554. doi: 10.1016 /j.jom.2007.06.007

Shah, R., Chandrasekaran, A., & Linderman, K. (2008). In pursuit of implementation patterns: the context of Lean and Six Sigma. *International Journal of Production Research, 46*(23), 6679-6699. doi: 10.1080/00207540802230504

Smetkowska, M., & Mrugalska, B. (2018). Using six sigma DMAIC to improve the quality of the production process: A case study. *Procedia – Social and Behavioral. Sciences, 238*, 590-596. doi: 10.1016/j.sbspro.2018.04.039

STN EN ISO 9001:2015. Quality Management System (QMS). Requirements.

Trend. https://www.etrend.sk

Vest, J. R., & Gamm, L. D. (2009). A critical review of the research literature on six sigma, lean and studergroup's hardwiring excellence in the US: The need to demonstrate and communicate the effectiveness of transformation strategies in healthcare. *Implementation Science, 4*(35). doi: 10.1186/1748-5908-4-35

Vinodh, S., & Swarnakar, V. (2015). Lean Six Sigma project selection using hybrid approach based on fuzzy DEMATEL–ANP–TOPSIS. *International Journal of Lean Six Sigma*, *6*(4), 313-338. doi: 10.1108/IJLSS-12-2014-0041

Wang, C. H., Tseng, M. L., Tan, K. H., & Yu, K. T. (2017). Application of a mathematical programming model to solve the confidence interval. *International Journal of Information and Management Sciences, 28*(1), 11-23.

Yerriswamy, W., Swamy D. R., & Nagesh, P. (2014). The process capability analysis – a tool for process performance measures and metrics - a case study. *International Journal for Quality Research*, *8*(3), 399-416.

Volume 13 • Issue 2 • 2021

sciendo

ISMSME International Society for Manufacturing, Service and Management Engineering

received: 10 February 2021
accepted: 1 August 2021

pages: 50-65

Critical evaluation into the practical utility of the Design of Experiments

Mithun Sharma Shilpi Sharma

A B S T R A C T

The research aims to emphasise the relevance of the Design of Experiments (DOE) technique as a reliable method for ensuring efficient use of statistical methods in routine industrial processes. A case study approach with a deductive strategy was used to assess the effectiveness of different DOE methods to achieve the desired objectives. Screening, mid-resolution and high-resolution DOE methods helped identify, characterise, and optimise an experimental variable against the desired output response. A general framework for effective DOE is provided as part of DOE planning, including defining DOE objectives, selection criteria, noise reduction, and application across industries. Overall, various DOE models proved successful in identifying a complicated relationship between experimental variables and output response. However, when ideal DOE models may not be feasible, reducing test run by choosing lower resolution DOE or fewer replicates can still provide important insights into the experimental variables' impact on output responses.

K E Y W O R D S

Six-Sigma, Design of Experiments, screening, Taguchi screening, full factorial

10.2478/emj-2021-0021

Mithun Sharma

O.P. Jindal Global University, India
ORCID 0000-0002-0108-6331

Corresponding author:
e-mail: mithun.sharma@gmail.com

Shilpi Sharma

O.P. Jindal Global University, India
ORCID 0000-0003-4316-8551

Introduction

Presently, the world is in a state of pandemonium, disordered and frenzied, which makes the work of scientists and engineers formidable. Evolving new products, advancing old models, managing ongoing processes, and repairing gadgets are some of the many routine technical tasks for engineers. Daily life is contingent on engineers' real-life technical activities, which are highly complex, multi-staged processes. The engineering field is continuously under

Sharma, M., & Sharma, S. (2021). Critical evaluation into the practical utility of the Design of Experiments. *Engineering Management in Production and Services, 13*(3), 50-65. doi: 10.2478/emj-2021-0021

pressure to re-engineer its process-control mechanisms to keep up with the exponentially increasing advancements in new technology to prevent lags in the process yield quality. To be a frontrunner and beat the business competition, engineers must step up from simple solutions to analysing complex interactions stemming from a thousand different factors. The success of any complex process is contingent on experimental testing, process control, and statistical analysis. Unfortunately, training in advanced statistical techniques is not a regular part of engineering qualification in most countries, which raises serious questions about the accuracy of the analysis most engineers are obliged to perform (Bisgaard, 1991). In this context, the Design of Experiments (DOE) is an efficient tool for applying statistics to routine experimental manufacturing tasks (Davim, 2016; Lye, 2005).

DOE is a toolkit, a set of guidelines that offers several statistical tests for managing resolute modifications to more than one input variable in an engineering process and assessing its impact on the resulting outputs (Montgomery, 20017). It is a cost-effective and time-saving quality improvement technique for managing and optimising processes across various industries. The DOE qualified as a distinguished class of its own and was an independent toolkit during the twentieth century but is now a part of the trendy Six-Sigma package (Brady & Allen, 2006). This paper emphasises the relevance of the DOE technique as a reliable method for ensuring efficient use of statistical methods in routine industrial processes. The following sections of the literature review present more information on the nature, stages, and types of DOE techniques, their benefits over the traditional experimental methods, their relevance to the Six-Sigma methodology, the wide applications of DOE across various industries, and the gaps in its current use. This is followed by results from multiple DOE categories across different sectors to gain practical insights into the process shared in the discussion section of the manuscript.

1. Literature review

1.1. What is DOE?

The design of experiments (DOE) technique relies on several statistical methods to optimise the modelling of various factors and response variables simultaneously (Hecht et al., 2016). DOE's origin date back to 1926, whereby Ronald E. Fisher used it to systematically eliminate environmental biases from a geometrically patterned agricultural field experiment (Fisher, 1926). The principles used in this first design construction have emerged as pillars of statistics. Many of his predecessors defined the importance of replication in understanding variation, including William's student Gosset. Fisher and his contemporaries, such as Stuart Chapin (1950, randomisation) and Wald and Tukey (1943 and 1947, respectively, blocking), elaborated on DOE applications in many other industries. Later in the 21st century, many other statisticians, such as Box et al. (1987) and Montgomery (2017), further strengthened the DOE technique's mathematical foundations, providing a reliable platform to engineers and other practitioners.

The application of DOE models is known to benefit a wide range of industries, such as Aviation (Yondo et al., 2018; Davis et al., 1996), Service (Antony et al., 2020; Setamanit, 2018), Chemical Engineering (Yoo, 2020; Durakovic & Torlak, 2017; Andersson et al., 1996), Engineering (Schlueter & Geyer, 2018), Environment (Okatia et al., 2016; Yang & Tsai, 1998), Food Technology (Yu et al., 2018; Chen, 1996), Manufacturing (Wesling & Emamjomeh, 1994), Materials (Paulo et al., 2017; Bucher & Loos, 1994), Medical (Yip et al., 2020; Mager, 1997), and Microbiology (Puente-Massaguer et al., 2020). Within the field of engineering and science, DOE's applications are frequently visible in the materials sector (30 %), mechanical engineering (18%), chemical engineering (17 %), and the industrial sector (13 %).

1.2. Basic principles of Design of Experiments

Every process, manufacturing or service will inevitably experience variation resulting in rejects or failures. These variations could stem from different testing temperatures or even concentrations, types of raw materials, and adjustments of process parameters across different testing sessions. Controlling such variations is expensive and time-consuming, and some processes might be more sensitive than others. Thus, the aim is to identify the sources of such manufacturing variations and control them by setting appropriate process controls, reducing the process sensitivity, and improving output quality (Kackar & Shoemaker, 2021). To do that, an engineer needs three types of information: a) general, measurable metrics that may indicate functional characteristics

of the final product, b) process engineer also needs exact parameters for the process variables so that they can manipulate their standard settings, and c) uncontrollable external environmental sources of noise, such as the factory's humidity and temperature. Thus, the objective is to identify control parameter settings that minimise the noise factor effect on functional characteristics of the final output. The whole step-by-step model is a robust design, first discussed by Taguchi as a quality control strategy (Antony & Roy, 1999). The DOE strategy works on a similar model to identify the underlying causes of process problems. It is a disciplined approach that systematically manipulates settings of the control parameter variables to minimise the noise effect on the functional characteristics of the output (Gardner & Bieker, 2000).

While applying the DOE model in a process, engineers may have to deal with two kinds of process variables that they need to manipulate for reducing noise effects on the final output: quantitative and qualitative. Quantitative settings are measurable goals, controllable, and usually pre-determined across different levels of process settings. The term "level" refers to settings or process specifications for a factor in an experiment. Technical specifications of a particular manufacturing process constitute these variables. On the other hand, qualitative variables are external, disconnected, and may require many more levels than a quantitative factor. Type of supplier, characteristics of a catalyst, and the composition of raw materials are examples of qualitative factors in a manufacturing process. In a standard DOE, an engineer performs a pre-determined number of trials to assess the effects of different variable levels on an outcome variable.

Three frequently used stage-wise processes in experiments to enhance the output efficiency statistically and significantly and minimise bias are: a) randomisation is an essential building block of statistical methods in experimental designs. It is the process of randomly assigning factors to testing units to ensure an equal probability of each factor's allocation to any one test; b) replication enables an experimenter to estimate the experimental error by simple repetition of necessary tests; c) blocking further enhances an experimental design's efficiency by grouping homogeneous experiments and controlling any extraneous variation sources.

In essence, the DOE aims to detect optimum and efficient solutions to process problems through systematic planning, designing, and statistically analysing engineering experiments. The success of an industrially designed experiment depends on efficient planning, accurate design choice, thorough statistical analysis of the data, and collaborative teamwork. Traditionally, engineers heavily relied on the one-factor-at-a-time (OFAT) technique for their experimental needs. The OFAT technique draws on a null hypothesis that no difference exists between two settings of a manufacturing process parameter, and it sequentially tests all the inherent factors, one at a time.

1.3. OFAT vs DOE

The most significant risk of using the OFAT technique is its failure to identify the real optimum value and ignoring the potential interactions between different factors. Another difficulty in using the OFAT technique is its inability to separate the process's inherent noise from the actual test improvement. Therefore, a viable alternative is the DOE technique, enabling simultaneous combinatorial testing of all factors in a full factorial design model. If there are "k" number of factors and "X" numbers of levels within a testing range, then a DOE strategy will allow for "Xk" number of experiments (Hecht et al., 2021). This strategy produces novel reaction conditions and provides for the systematic elimination of researcher bias. Other noted advantages of DOE over the traditional OFAT technique (Czitrom, 1999): a) it requires fewer resources, such as time, material, and the number of experiments for the amount and quality of results it produces, b) the estimated effects of each factor on the response variables are exact, and it can yield information on a larger region of the factor space. DOE has proven to offer substantial financial benefits by improving a product's yield and quality by its use at three different times in the life of a manufacturing process: a) to determine the optimal testing conditions in the early days of initiating a process, b) to establish the robustness of a methodology for formal applications to regulatory agencies, and c) for refining existing conditions of already known procedures.

The DOE technique further gains a significant edge over OFAT by carrying out multiple testing involving several factors and simultaneously assessing their impact on the product yield and quality. The DOE technique can also isolate the interdependent effects of a combination of factors, if any, by testing the results using appropriate statistical methods. The most commonly used statistical techniques are analysis of variance (ANOVA), half-normal and contour

plots, and response surface methodology. Nowadays, statisticians and technical professionals across many industries acknowledge the practical utility of DOE as an indispensable quality improvement tool. It is also a part of one of the most popular business world philosophies: the Six-Sigma methodology.

1.4. Design of Experiments as a key tool of Six-Sigma

Six-Sigma is a quality improvement tool that consists of a systematic and organised set of scientifically proven statistical methods for defect reduction in a product and carrying out strategic improvements in a process thereby improving customer satisfaction. The stellar popularity of the Six-Sigma technique as a quality improvement methodology relies upon its scientifically organised and data-driven statistical approach (Hahn, 2005), which has proven to be a winning combination time and again. A general stepwise sequence of a Six-Sigma practitioner consists of five logical stages of Define, Measure, Analyse, Improve, and Control, popularly known as DMAIC. It starts with delineating the project scope and measurable goals, followed by identifying specific characteristics of the process. The following two stages of Measure and Analyse gauge the process attributes for an efficient implementation during the Improvement phase in a manner that leads to sustainable, long-term benefits, monitored under the final Control stage (Goh, 2002). The most critical and bulky steps for achieving the project's goals are the Analyse and Improve phases, which rely on experimentation, thus creating a perfect niche and fit for the DOE technique. The various stages of a DOE are further elaborated in the next section.

Stage 1. First and foremost, engineers agree on the broad aims, specific objectives, and the input and output variables for the intended experiments. According to Wu and Hamada's classification system, there are three ways of conducting this first stage. The first type is the traditional approach and mainly concerns the screening and characterisation stages in a process. The second type of DOE referred to as the response surface methodology (RSM), is intended to understand process behaviour and find the optimal performance point (Myers et al., 2004). The third type borrows from Taguchi's principles and focuses on detecting those controllable process settings that will effectively minimise the variability induced by noise factors, known as the robust parameter design (RPD) (Robinsson et al., 2003).

Stage 2. The next stage delves into the specification of the different levels of the previously selected input variables for the manufacturing experiment. Often engineers rely on their expert knowledge and experience for agreeing on the number of factors and their levels during this stage.

Stage 3. A range of experimental design options is available for use in a DOE engineering model. The most popular (31 %) is Taguchi's orthogonal matrices, consisting of tables to display experiments for specific constituents of factors. The next common choice (16 %) among manufacturing practitioners is full factorial designs that produce an exhaustive list of all possible combinations for every single factor and their level. Another common (14 %) type of experimental design is fractional factorial, i.e., the design, which carefully selects and conducts only fractions of the full factorial design experiments. Finally, central composite designs (9 %) enhance several factorial design experiments with axial and centre points. Other less popular designs are Placket-Burmann (4 %) and optimal designs (4 %). The Taguchi method's higher popularity amongst engineers is partly due to its solid statistical base that significantly enhances its practicality (Box, 1988; Nair, 1992). However, due to a lack of statistical training amongst most engineers, manufacturing industries still fail to capitalise on the robust methodology and often rely on other designs, such as orthogonal matrices, full or partial factorial designs.

Stage 4. After selecting the number of factors, their levels, and the number of design options, engineers contemplate and set the number of experiments they need. This decision is usually contingent on the available budget, access to resources, and the engineers' expertise combined with the previous variables of the type of design and factors.

Stage 5. The final decision relates to a real or simulated computer experiment. An actual, tangible experimental process using factual data usually occurs in a laboratory or manufacturing plant, and a simulated option can be through computer software. Computer simulated experiments for product and process development have recently gained tremendous popularity (Kennett & Steinberg, 2006). A simulation is cost-effective as it facilitates simultaneous testing of many factors and proves to be especially useful in case an experiment turns out to be defective.

Gaps in the current research. It is noticeable that despite a steep rise in the number of scientific articles using the DOE technique, there is a gap in the effec-

tive use of advanced statistical analyses. For example, between 2003 – 2007, there were about six publications per year, which increased by 145 %, to 14.7 publications/year for the next five-year period of 2008 – 2013. However, a significant proportion of engineering publications (at least 77 in the last five years) suggested low use of advanced statistical techniques. Furthermore, many scientific articles excluded relevant details of the pre-experimental steps, potentially reducing the educational value of the publications. Therefore, the scientific community should invest more tremendous efforts in conquering the valley between the engineering community and the statisticians. One of the ways is to provide a practical DOE framework with statistics aiding and not restricting the process.

This paper aims to provide the general framework with critical consideration to improve the effectiveness of the DOE in industrial applications. Furthermore, as the same personnel led the DOEs, it removed user variation and evaluated different DOEs objectively across industries. This is a novel idea as all the previous comparative DOE-related research publications have been independent or restricted to a single sector.

2. Research methods

We present a comparative evaluation of the utility of three distinct categories of DOE, conducted across a wide range of industries. These three types are also the most common forms of a DOE design:

- Screening,
- Mid-Level Resolution, and
- High Resolution or Response Surface Designs.

Many factors influence the creation of DOE, and hence the framework below was adopted and recommended to increase its effectiveness.

1. Define the problem. Explain the issue to be resolved or understood using the experimental designs.

2. Establish the objective. State the purpose of the DOE, i.e., to identify significant input variables, identify an interaction between variables, or characterise and optimise them.

3. Select the output. Decide how to measure the performance.

4. Select the input factors and their levels. Use the CNX (Controlled Noise eXperimental) diagram (Fig. 2) to help select experimental input factors. Controlled input factors remain constant and experimental factors are changed as per DOE to evaluate their impact on the output. The effect of noise factors should be minimised during the DOE.

5. Select the experimental design & sample size. Below are some of the factors that should be considered while selecting the DOE.

- Aims and objectives of the experiment. An essential consideration in selecting a DOE is whether the intention is to use it to identify significant input variables only or characterise and optimise input variables.
- The number of input variables. Typically, in the case of input factors higher than six, a screening design is more appropriate; for a design involving less than six input variables, industries prefer a mid-level resolution design; and for processes inputting between two and four factors, the full factorial design is the optimal choice.
- The number of levels and replicates. The number of input factor levels helps characterise its relationship with the output, especially a non-linear relationship. Replicates can be used.
- Calculate pure error derived from the measurements. Ideally, the more the input factor levels and replicates, the better it is for DOE. Still, considering the DOE practicality, it may not always be possible to opt for the ideal design.
- Randomisation protects against unknown or uncontrolled input variables.

6. Collect the data: Once the test plan is created, perform the tests and collect the response/output data.

7. Analyse the data. Standard statistical software like Minitab can be used to analyse the DOE data in detail, helping in identifying, characterising and optimising significant input factors and their interactions.

8. Draw conclusions. Based on the analysis, make conclusions to help with the design and development of permanent corrective action.

9. Evaluate whether all objectives were achieved or not. If not, a follow-up DOE might be required.

Following the above framework, vital outcomes from various DOEs were present. They were conducted across different industries under three broad categories: Screening, Mid-Resolution and High-Resolution Designs. The utility of different DOEs was analysed based on their effectiveness and efficiency in meeting the desired objectives. The same personnel led these experimental designs eliminating the noise from operator variation due to skillset and methodology.

3. Research results

3.1. Screening designs

A screening DOE is used to gain insights between experimental inputs and outputs in cases when many experimental variables are present. To elucidate current research objectives, a couple of examples were taken from electronics wafer manufacturing and the wireless communication industry.

3.1.1. Poor Li-Fi connection speed

An L36 (2^3, 3^3) Taguchi DOE was used in a warehouse logistic company to identify factors affecting connection speed between two devices communicating wirelessly via Light Fidelity (Li-Fi) technology. There were six experimental factors with multi-level input values. The example presented here was one of many screening DOEs conducted to gain insight into a large pool of potential Key Process Input Variables (KPIVs). Higher-resolution DOE would have required thrice the experimental runs, which was not practical considering the experiment's effort. The process's knowledge helped select a Taguchi design that evaluated potentially significant factors and interactions among the factors. The main effects plot and response ranking for the mean connection speed is shown in Fig. 1 and Table 1, respectively.

Taguchi DOE was successful in identifying the key factors affecting the connection speed. The optimum settings, calculated using Minitab's predict Taguchi results, yielded low connection speed when used during confirmation testing. For this reason, we recommend a follow-up using a screening DOE with a high resolution fractional or full factorial DOE. Results from the full factorial DOE are discussed below. We suggest that the top four factors from Taguchi DOE should be statistically significant in determining mean connection speed, but characterisation plots are likely to be different.

3.1.2. Electronics wafer manufacturing

It is an industry where conducting experimental design is very valuable but also very expensive. Each test run costs approx. GBP 500, which made it critical to keep the experimental runs as low as possible. Even before considering DOE, a detailed analysis of the existing data was conducted to reduce potential KPIVs from 40 to nine. However, nine was still too high to conduct a high resolution or more than 2-level DOE. For Taguchi or any DOE to be successful, care-

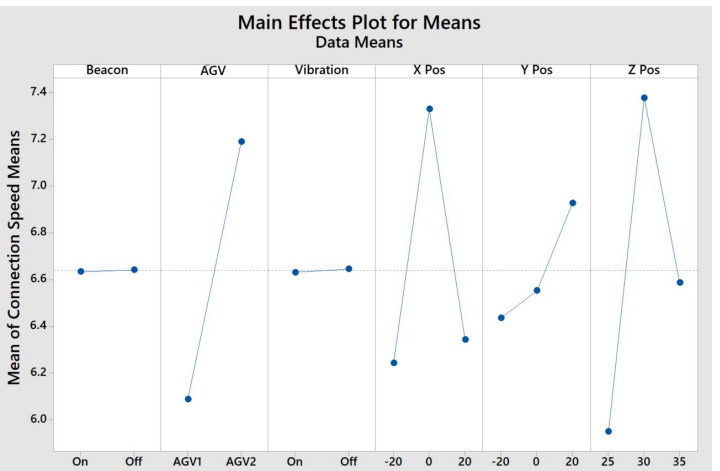

Fig. 1. Main effects plot for mean connection speed

Tab. 1. Response for mean connection speed

Level	Beacon	AGV.	Vibration	X Pos	Y Pos	Z Pos
1	6.634	6.088	6.632	6.243	6.437	5.951
2	6.642	7.190	6.646	7.329	6.553	7.378
3				6.344	6.927	6.587
Delta	0.008	1.102	0.014	1.087	0.490	1.426
Rank	6	2	5	3	4	1

ful selection of KPIVs levels, managing and controlling the noise variables are critical. A reasonable understanding of the KPIVs through the Six-Sigma methodology helped create a detailed CNX diagram shown in Fig. 2.

We used a Taguchi L12 design to rank the input factors in the order of their impact on TTV. Taguchi L12 implied that by performing 12 lapping batches, nine experimental factors at two different values were evaluated for their effects on TTV, as shown in Fig. 3 and Table 2.

From Taguchi DOE, the top two ranking factors (the sun gear ratio and plate temperature) seemed to impact TTV significantly. Moreover, the bottom plate speed, with a ranking of three, did not appear to be significant but was still included in the further analysis; because Taguchi is only a screening DOE, so a follow-up with a more comprehensive DOE to

Tab. 2. Response for Means

Level	Sun Gear Ratio	Bottom Plate Speed	Exhaust Timer	Acceleration Timer	Plate Temp.	Recycle Slurry Status	Active agent concentration	Slurry Temp.	Slurry Mixing Time
1	1.2893	1.0338	1.0053	1.0092	1.1997	0.9940	1.0120	0.9957	1.0062
2	0.7123	0.9678	0.9963	0.9925	0.8020	1.0077	0.9897	1.0060	0.9955
Delta	0.5770	0.0660	0.0090	0.0167	0.3977	0.0137	0.0223	0.0103	0.0107
Rank	**1**	**3**	9	5	**2**	6	4	8	7

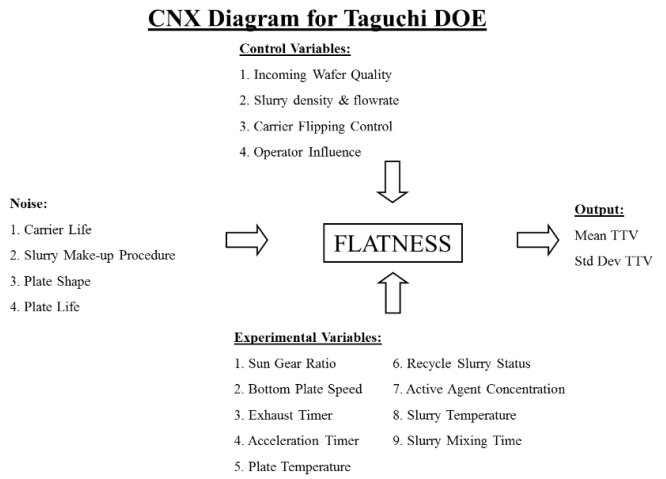

Fig. 2. CNX diagram for DOE

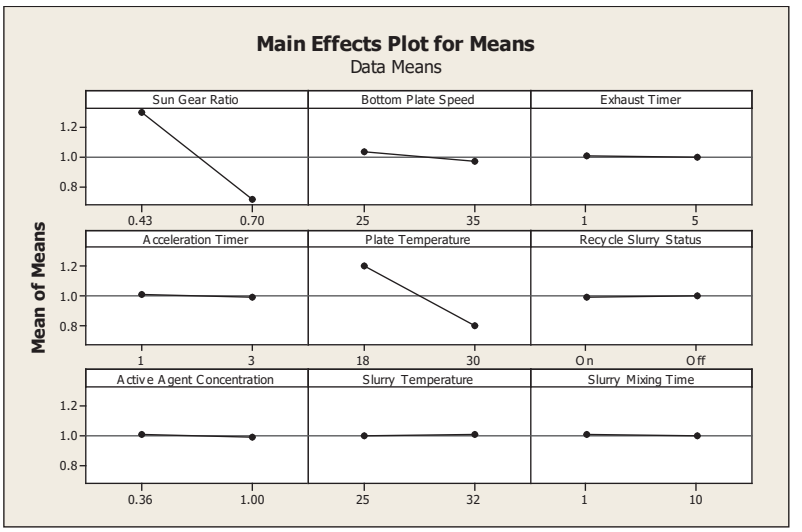

Fig. 3. Main effect plots for means

confirm the results of screening DOE is usually recommended.

3.2. Mid-Resolution Designs

Mid-Resolution Designs are an optimal choice when the interaction between KPIVs is significant to the theoretical model while keeping the experimental runs to a minimum. In this section, a couple of examples are presented from the same industry.

3.2.1. The plumbing industry

This set of fractional factorial experimental designs was conducted in a UK-based, global plumbing company renowned for its bathroom products. A soon-to-be-launched mixer shower product was demonstrating a high reject rate for leak failures. The product consisted of 12 sub-assemblies and components that went through five assembly stations and two leak tests at different assembly stages. At the final leak stage, approx. 12 % of the product was rejected for a high leak rate resulting in a high financial loss due to scrap and rework. After the initial root cause analysis, the team identified six potential factors with possible interactions. A quarter-factorial of two levels with resolution IV and a 20 test run design was deemed most suitable for the purpose. Centre points were also added to identify the possible non-linearity of the KPIVs. The output from the variance analysis and model summary is presented in Table 3, and the Pareto chart is shown in Fig. 4.

The response data were categorised based on visual inspection, which was an interesting attempt to evaluate the effectiveness of DOE against ordinal

Tab. 3. Analysis of variance and model summary

Source	DF	Adj SS.	Adj MS	F-Value	P-Value
Model	17	236.700	13.9235	26.52	0.037
Linear	6	116.200	19.3667	36.89	0.027
Housing	1	72.250	72.2500	137.62	0.007
Cover	1	0.450	0.4500	0.86	0.452
Energy	1	12.250	12.2500	23.33	0.040
Working Pressure	1	9.000	9.0000	17.14	0.054
Standstill Delay	1	6.250	6.2500	11.90	0.075
Amplitude	1	16.000	16.0000	30.48	0.031
2-Way Interactions	8	84.250	10.5312	20.06	0.048
Housing*Cover	1	0.250	0.2500	0.48	0.561
Housing*Energy	1	25.000	25.0000	47.62	0.020
Housing*Working Pressure	1	0.250	0.2500	0.48	0.561
Housing*Standstill Delay	1	25.000	25.0000	47.62	0.020
Housing*Amplitude	1	20.250	20.2500	38.57	0.025
Cover*Working Pressure	1	0.250	0.2500	0.48	0.561
Cover*Amplitude	1	12.250	12.2500	23.33	0.040
Energy*Standstill Delay	1	0.000	0.0000	0.00	1.000
3-Way Interactions	2	90.450	45.2250	86.14	0.011
Housing*Cover*Amplitude	1	36.000	36.0000	68.57	0.014
Cover*Energy*Standstill Delay	1	54.450	54.4500	103.71	0.010
Curvature	1	0.000	0.0000	0.00	1.000
Error	2	1.050	0.5250		
Total	19	237.750			

S	R-sq	R-sq(adj)	R-sq(pred)
0.724569	99.56%	95.80%	24.06%

response data. An excellent R-sq value suggested an ideal regression model. Significant KPIVs were identified from the model, and an optimum setting was established using the Minitab software. Confirmation testing validated the theoretical model.

3.2.2. Robustness of the optimum settings

The optimum settings derived in the previous section need to work for different batches of three key components, which are housing, cover, and base. Although visual check (Attribute Data) indicates weld quality, burst strength (continuous data) is the correct measure that required destructive testing. Considering the total loss of a part due to destructive testing, a half-factorial, two-level, and resolution III was conducted with these three factors. The variance analysis results are shown in Table 4 and the Pareto chart in Fig. 5.

We obtained excellent experimental design results with a 100 % R-sq value and no factors exerting a statistically significant burst strength impact. However, further analysis revealed that the DOE could not calculate p-value and R-sq (adj), suggesting some missing data links. Visual inspection of the weld further revealed quality issues with certain parts. As this was a compliance and safety issue, a full factorial DOE technique was performed with one replicate using the same input variables. The results are presented in section 3.3.1. It was also found that although it was a fractional factorial DOE, the resolution was only III, which had put it into the screening DOE category and hence less useful in characterising the factors.

3.3. High-Resolution Full factorial designs

High-Resolution Full factorial designs are complete models with quadratic interactions for identification, characterisation, and optimisation of KPIVs.

This is the follow up full factorial DOE technique to the Taguchi screening discussed earlier in section 3.1.1. A four-factor and two-level full factorial DOE was performed with centre points using experimental factors identified from the screening DOE. The main effects plot and model summary generated using Minitab selecting stepwise options are shown in Fig. 6 and Table 5.

All four experimental variables and a two-level interaction were found to be statistically significant. A robust regression model, R-sq (Adj) of 90.61 %, was

Tab. 4. Analysis of variance and model summary

Source	DF	Adj SS.	Adj MS	F-Value	P-Value
Model	3	6.68750	2.22917	*	*
Linear	3	6.68750	2.22917	*	*
Housing	1	1.56250	1.56250	*	*
Base	1	0.06250	0.06250	*	*
Cover	1	5.06250	5.06250	*	*
Error	0	*	*		
Total	3	6.68750			

S	R-sq	R-sq(adj)	R-sq(pred)
*	100.00%	*	*

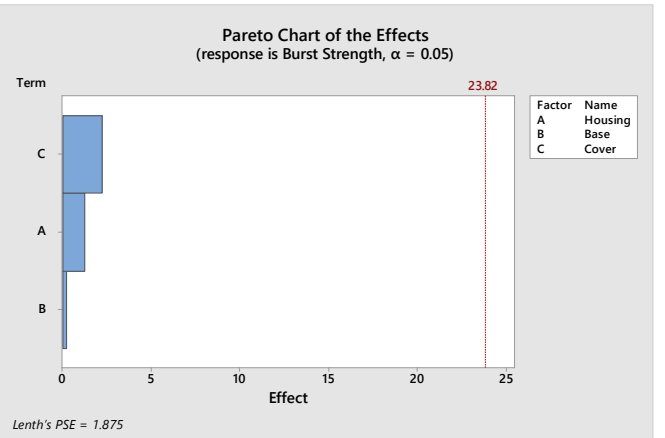

Fig. 5. Pareto chart of the effects

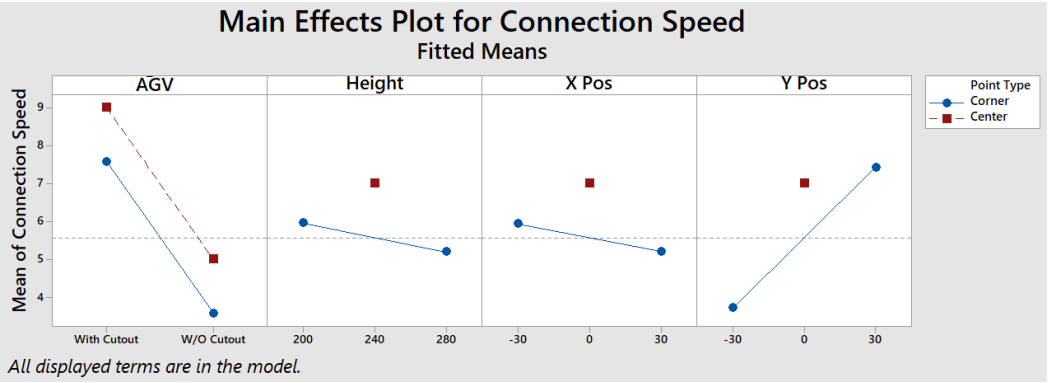

Fig. 6. Main effects plot for mean connection speed

Tab. 5. Model summary and coded co-efficient for connection speed

S	R-sq	R-sq(adj)		R-sq(pred)		
0.929010	91.56%	90.61%		88.99%		
Term	**Effect**	**Coef**	**SE Coef**	**T-Value**	**P-Value**	**VIF.**
Constant		5.579	0.147	37.98	0.000	
AGV	-3.992	-1.996	0.120	-16.64	0.000	1.00
Height	-0.757	-0.378	0.147	-2.58	0.013	1.00
X Pos	-0.720	-0.360	0.147	-2.45	0.018	1.00
Y Pos	3.702	1.851	0.147	12.60	0.000	1.00
AGV*Y Pos	2.860	1.430	0.147	9.74	0.000	1.00
Ct Pt		1.436	0.254	5.64	0.000	1.00

achieved with a combination of four factors tested during the experiment suggesting that most of the process variation can be controlled via these factors. With the help of Minitab's Response Optimiser, optimum settings were identified, including tolerances, for all the factors. It helped develop a robust solution that can deal with manufacturing, installation, and operational variations between the two AGVs without significantly affecting connection speed. It is essential to highlight that some of the obtained settings differed from what was identified during the screening phase, further highlighting the potential shortcomings of screening DOE. Pilot testing was conducted with the new set-up using single Li-Fi, but multiple AGVs. Achieved process capability (Cpk) of 3.18 was much higher than the industry standard of 1.67, which also confirmed the solution's robustness.

This is the follow up full factorial DOE to the Taguchi screening discussed earlier in section 3.1.2. Three-factor and two-level full factorial DOE with centre points was designed to characterise and optimise the three experimental factors. The DOE successfully identified statistically significant factors and the effect of their interactions on the output (Fig. 7). The factors above the red line were statistically significant, and the factors below were non-significant.

The main effects plot shown in Fig. 8 indicated that an increase in the sun gear ratio, plate temperature and the bottom plate speed resulted in reduced TTV. Further, as centre points (marked red) for all the three factors were not on the line, the impact of these factors on TTV was non-linear. For example, the plate temperature increase to 24 °C did not reduce TTV; however, a plate temperature closer to 30 °C was most likely to reduce the TTV reject rate.

Results from Minitab's Response Optimiser are shown in Fig. 9, suggesting that to achieve the minimum TTV (0.462), inputs should be set to the parameters highlighted in red.

The theoretical predictive DOE model was validated via a confirmation run using the recommended input values that yielded similar results to the DOE model.

This is the follow up full factorial DOE to the fractional factorial DOE discussed earlier in the plumbing industry section 3.2.2. A three-factor and two-level full factorial DOE with a replicate was conducted. The results of the Pareto chart of the standardised effects are shown in Fig. 10.

In contrast to fractional factorial DOE, the full factorial DOE was able to identify "housing" as a statistically significant factor. The same full factorial

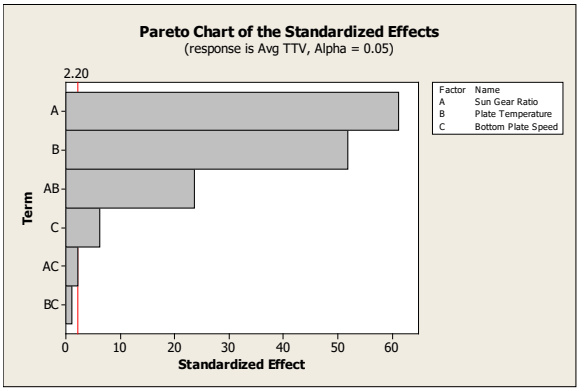

Fig. 7. Normal and standardised effects for Pareto charts

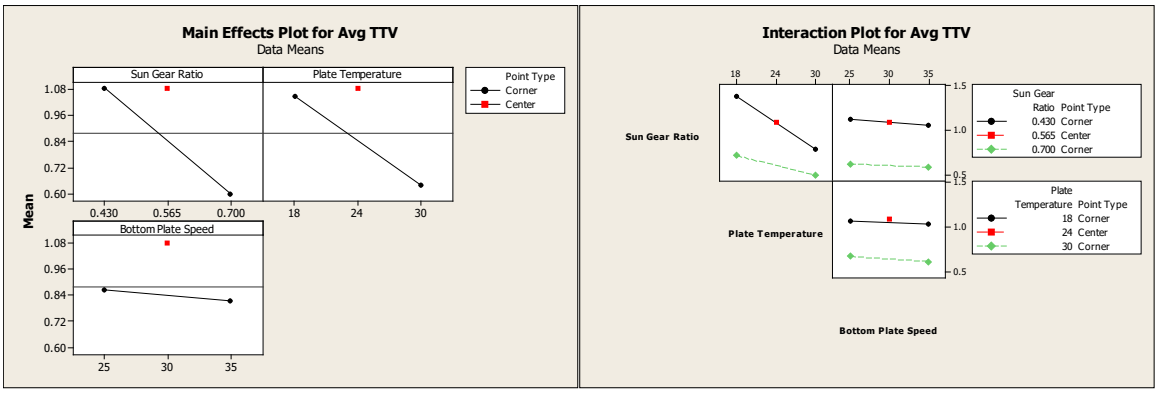

Fig. 8. Main effects and interaction plots for Avg TTV

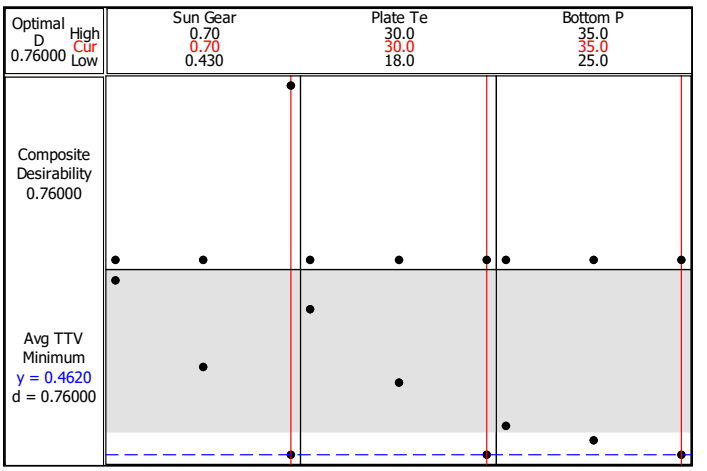

Fig. 9. Response optimiser result

DOE model without replicates was analysed as an academic exercise, presented in Fig. 11. It can be seen that without replicates, even the full factorial DOE model failed to detect any significant factors. Investigating it further revealed that high variation in the burst strength measurements made it challenging to identify process shifts. In such cases, it is recommended to have as many replicates as possible.

Based on the insights gained from the DOE, further investigation into two types of housing revealed that poor roundness of the low performing housing was responsible for reduced burst strength. Confirmation testing and the pilot study conducted using suitable housing provided similar results to the theoretical DOE model. Further data collected after the resolution of housing roundness also provided excellent results with no failures.

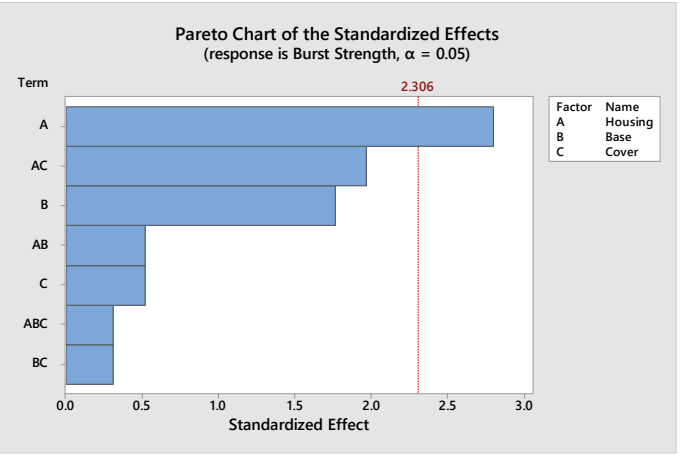

Fig. 10. Normal and standardised effects for Pareto charts (with a replicate)

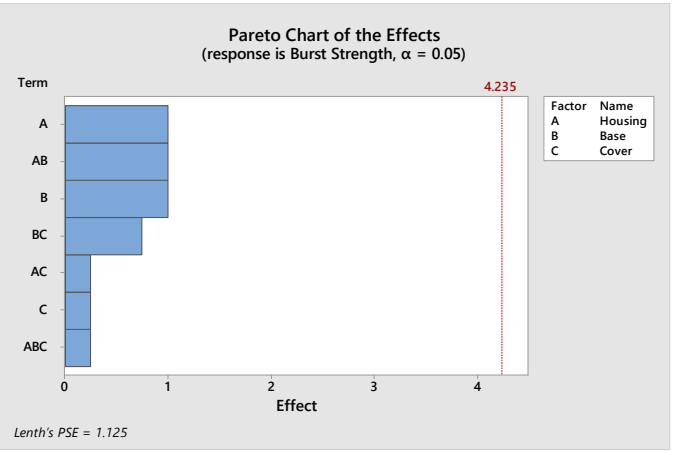

Fig. 11. Normal and standardised effects for Pareto charts (without a replicate)

3.4. Summary of various DOE results

Comparison between multiple DOE techniques and their utility is summarised in Table 6.

Tab. 6. Comparative summary of DOE results

DOE Type	Input Factors	Effort / Cost	Identifying KPIV & Interactions	Characterising KPIV & Interactions	Optimising KPIV & Interactions	Application
Screening	6,9	Low	KPIVs only	Not reliable	Not reliable	At the start of development or problem solving, where the number of potential input variables is high
Mid-resolution	3,6	Medium	KPIV & some of 2-way interactions	KPIV & some of the 2-way interactions with low error	Not reliable	The number of potential input variables is <9 with no 4-way or higher interactions
High-resolution	3,4	High	KPIV and up to all interactions	KPIV & up to all the interactions with very low error	Reliable	This should be the preferred choice as long as it is practical

4. Discussion of the results

In line with previous research (Ilzarbe et al., 2008; Antony et al., 1999; Hecht et al., 2016), various DOE models were highly influential in attaining the experiments' objectives. This research study found that defining the experimental designs' goals as part of DOE planning is vital. For example, a) Is DOE used for KPIVs identification only or to characterise and optimise KPIVs as well? b) Is the interaction between KPIVs significant? c) To what level must the KPIVs be characterised? However, DOE objectives may change if many tests are not feasible due to a large set of experimental factors and their levels. Every factor or level added in the full factorial design increases test runs significantly, calculated by FL where F is the number of factors, and L is the number of levels. For example, a 2-level and 3-factor will require 8 test runs compared to 27 test runs for a 3-level and 3-factor or 16-factors for a 2-level and 4-factor design. Similarly, a fraction factorial or screening DOE will use half or less than a full factorial design. As shown in Section 3, a less comprehensive DOE model must be chosen to achieve the initial objectives set out for experiments in such cases.

Consistent with previous research studies (Zheng et al., 2013; Robinson et al., 2003; Box, 1988; Box et al., 1988; Nair, 1992), it was found that screening DOEs were highly effective in identifying KPIVs while managing a high number of variables. In Section 3.1, both screening DOEs managed to identify statistically significant KPIVs, which remained the same even when conducted with higher resolution DOE. However, it was argued that screening DOE effectiveness was highly dependent on the user's skillset to choose the correct levels and screening model. Previous studies have highlighted the ineffectiveness of screening DOE in characterising the KPIVs. This paper confirmed this conclusion as the optimum setting derived from screening DOEs in both cases failed to give desired results during confirmation testing. As the name suggests, screening DOE can be good for identifying KPIVs, but not that useful for characterising and optimising them.

It is well established that the Design of Experiments is a powerful and versatile analytical tool that works across industries with different data types (e.g., Durakovic, 2017; Hecht et al., 2016; Ilzarbe et al., 2008). This research further elucidates that the DOE works with continuous variable data and ordinal response data. In Section 3.2.1, the response variable was a visual inspection which categorised ultrasonic weld quality. However, as a general rule, before any data analysis, data validation should be performed. In this case, a Measurement System Analysis (MSA) was performed using the agreement analysis to identify reproducibility and repeatability error. In both cases, the agreement between and within visual inspectors was more remarkable than 90 %. The case studies presented in Sections 3.2.2 and 3.3 also stresses the relevance of MSAs. High variation in the burst strength measurement made it difficult for various DOEs to create an accurate regression model. In line with previous research studies (Sukhthomya & Tannock, 2005), DOEs were found to remain effective when an independent variable was discrete or categorical. All the DOE cases discussed in this manuscript had either categorical or discrete data as an independent variable.

It is essential when performing a DOE that the noise factors are identified and minimised as much as possible (Kackar & Shoemaker, 2021; Gremyr et al., 2003). However, at times maybe inadvertently, noise can be introduced in the DOE. Previous research studies recommended randomising experimental runs to reduce the impact of noise factors on the DOE model (Hecht et al., 2016; Antony, 2014; Box, 1990). In Sections 3.1.2 & 3.3, a couple of factors (the slurry mixing time and the plate temperature) are time-dependent, meaning the longer a machine runs, the better they become. If a similar DOE without these experimental variables and a randomised test was administered, the first few test runs would have always resulted in a poor TTV regardless of the test set-up. Another way of reducing the impact of noise factors is by repeating test runs (Hecht et al., 2016; Antony, 2014). For example, in section 3.3, a measurement system variation for the process was acceptable (% Tolerance Variation: 19.88), but it was still too high for the DOE to accurately identify and characterise independent variables. In this case, replicates helped to form correct modelling.

In line with previous studies (Weissman & Anderson, 2015), it is highly recommended to undertake confirmation testing after any DOE. The larger the sample size, with normal process variation, the better it is for validation. With a couple of case studies presented in Sections 3.1.1 and 3.2.2, it was found that the characterisation of independent variables was way off the mark, and optimum settings did not give the desired results. Confirmation testing becomes even more critical when the understanding of a process is limited.

The availability of advanced statistical software has made the DOE application more accessible without great statistical expertise for users (Durakovic, 2017; Hibbert, 2012). Also, the Minitab software was found to be extremely helpful in selecting and analysing various DOEs. The stepwise function was repeatedly used to generate accurate regression models. The Response Optimiser was also very helpful in identifying optimum settings, including tolerances for the independent variable, especially significant interactions were present.

Conclusions

The current study aimed to emphasise the relevance of the DOE technique as a reliable method for ensuring efficient use of statistical methods in routine industrial processes. The cases presented in the manuscript led to the conclusion that DOE effectively achieves the desired objectives. The DOE model should be selected based on the goals, i.e., screening, identifying, characterising or optimising KPIVs and their interactions. DOE is a powerful and versatile analytical tool that works across industries with different data types. However, if noise factors are not appropriately managed, it can easily result in inaccurate regression models. Randomisation and replicates are a couple of acceptable practices to reduce noise. Further, to avoid following the incorrect DOE conclusions, confirmation testing after any DOE is highly recommended.

Overall, various DOE models proved successful in identifying a complicated relationship between experimental variables and output. The different cases presented in the research study were conducted by the same person with a decent knowledge of the experimental product or process. It will, therefore, be useful for future research to try evaluating the impact of personnel and lack of product or process knowledge on DOE effectiveness.

Acknowledgements

The publication of the article for 11th International Conference on Engineering, Project, and Production Management - EPPM2021 was financed in the framework of the contract no. DNK/SN/465770/2020 by the Ministry of Science and Higher Education within the "Excellent Science" programme.

Ministry of Science and Higher Education
Republic of Poland

Literature

Andersson, P. M., Lundstedt, T. & Abramo, L. (1996). Synthesis and optimisation of 1-pyrrolemethane sulfonate by means of experimental design. *Journal of Chemometrics, 10,* 379-384.

Antony, J. (2014). Some Useful and Practical Tips for Making Your Industrial Experiments Successful. In J. Antony (Ed.), *Design of Experiments for Engineers and Scientists. Second Edition* (pp. 113-123). Elsevier. doi: 10.1016/B978-0-08-099417-8.00008-0

Antony, J., & Roy, R. K. (1999). Improving the process quality using statistical Design of experiments: A case study. *Quality Assurance, 6*, 87-95.

Arnoldsson, K. C., & Kaufmann, P. (1994). Lipid class analysis by normal phase high performance liquid chromatography, development and optimisation using multivariate methods. *Chromatographia, 38,* 317-324.

Beijersten, I., & Westerlund, D. (1995). Derivatisation Of Dipeptides With 4-Fluoro-7-Nitro2,1,3 Benzoxadiazole For Laser-Induced Fluorescence And Separation By Micellar Electrokinetic Chromatography. *Journal of Chromatography, 716*, 389-399.

Bisgaard, S. (1991). Teaching Statistics to Engineers. *The American Statistician, 45*(4), 274-283.

Bisgaard, S. (1992). Industrial use of statistically designed experiments: Case study references and some historical anecdotes. *Quality Engineering, 4*, 547-562.

Box G. E. P., Bisgaard, S., & Fung, C. (1988). An explanation and critique of Taguchi's contributions to quality engineering. *Quality and Reliability Engineering International, 4,* 123-131.

Box, G. E. P. (1988). Signal-to-noise ratios, performance criteria, and transformation. *Technometrics, 30,* 1-40.

Box, G. E. P. (2001). Statistics for discovery. *Journal of Applied Statistics, 28*(3-4), 285-299.

Box, G. E. P., Hunter, W. G. J., & Hunter, S. (1987). Statistics for experimenters: an introduction to Design,

Brady, J. E., & Allen, T. T. (2006). Six Sigma literature: A review and agenda for future research. *Quality and Reliability Engineering International, 22,* 335-367.

Bucher, R. A., & Loos, A. C. (1994). Parametric statistical analysis of electrostatic powder prepregging. *Journal of Advanced Materials, 25*, 44-50.

Bzik, T. J., Henderson, P. B., & Hobbs, J. P. (1998). Increasing the precision and accuracy of top load-

ing balances: Application of experimental design. *Analytical Chemistry, 70,* 58-63.

Carlson, A. D., Hofer, J. D., & Riggin, R. M. (1997). Development of an optimised peptide map for recombinant activated human protein c by means of an experimental design strategy. *Analytica Chimica Acta, 352,* 221-230.

Chapin, S. F. (1950). Research note on randomisation in a social experiment. *Science, 112,* 760-761.

Chen, H. C. (1996). Optimising the concentrations of carbon, nitrogen and phosphorus in a citric acid fermentation with response surface method. *Food Biotechnology, 10*, 13-27.

Czitrom, V. (1999). One factor at a time versus Designed Experiments. *The American Statistician, 53*(2), 126-131.

data analysis, and model building. New York: Wiley.

Davim, J. P. (Ed.). (2016). *Design of Experiments in Production Engineering*. Springer International Publishing.

Davis, B. L., Cavanagh, P. R., Sommer, H. J., & Wu, G. (1996). Ground reaction forces during locomotion in simulated microgravity. *Aviation Space and Environmental Medicine, 67,* 235-242.

Durakovic, B. (2017). Design of Experiments Application, Concepts, Examples: State of the Art. *Periodicals of Engineering and Natural Sciences*, *5*(3), 421-439. doi: 10.21533/pen

Durakovic, B., & Torlak, M. (2017). Simulation and experimental validation of phase change material and water used as heat storage medium in window applications. Journal of Materials and Environmental Science, 8(5), 1837-1746.

Fisher, R. A. (1926). The arrangement of field experiments. *Journal of the Ministry of Agriculture of Great Britain, 33,* 503-513.

Gardner, R., Bieker, J., Elwell, S., Thalman, R., & Rivera, E. (2000). Solving tough semiconductor manufacturing problems using data mining. In Proceedings of IEEE/SEMI Advanced Semiconductor Manufacturing Conference and Workshop, 46-55.

Goh, T. N. (2002). The role of statistical Design of Experiments in Six Sigma: Perspectives of a practitioner. *Quality Engineering, 14*(4), 659-671.

Gremyr, I., Arvidsson, M., & Johansson, P. (2003). Robust Design Methodology: Status in the Swedish Manufacturing Industry. *Qualitative Reliability Engineering International, 19,* 285-293.

Hahn, G. J. (2005). Six Sigma: 20 Key Lessons Learned. *Quality and Reliability Engineering International*, *21*, 225-233.

Hecht, E. S., Oberg, A. L., & Muddiman, D. C. (2016). Optimising Mass Spectrometry Analyses: A Tailored Review on the Utility of Design of Experiments. *Journal of American Society of Mass Spectrometry, 27,* 767-785.

Hibbert, D. B. (2012). Experimental design in chromatography: a tutorial review. *Journal of Chromatography, 910*, 2-13.

Ilzarbe, L., Álvarez, M. J., Viles, E., & Tanco, M. (2008). Practical applications of design of experiments in the field of engineering: a bibliographical review. *Qualitative Reliability Engineering International, 24*, 417-428.

Kackar, R. N., & Shoemaker, A. C. (2021). Robust Design: A cost-effective method for improving manufacturing processes. *AT&T Technical Journal*, *65*, 39-50.

Kenett, R. S., & Steinberg, D. M. (2006). New frontiers in the Design of experiments. *Quality Progress, 39(8),* 61-65.

Lye, L. M. (2005). *Tools and toys for teaching design of experiments methodology*. In 33rd Annual General Conference of the Canada, Toronto, Ontario, Canada.

Mager, P. P. (1997). How design statistics concepts can improve experimentation in medicinal chemistry. *Medicinal Research Reviews, 17,* 453-475.

Montgomery, D. C. (2017). *Design and Analysis of Experiments*. John Wiley & Sons, Inc.

Myers, R. H., Montgomery, D. C., Vining, G. G., Borror, C. M., & Kowalski, S. M. (2004). Response surface methodology: A retrospective and literature survey. *Journal of Quality Technology, 36*(1), 53-77.

Nair, V. N. (1992). Taguchi's parameter design: A panel discussion. *Technometrics, 34,* 127-161.

Okatia, V., Behzadmehra, A., & Farsad, S. (2016). Analysis of a solar desalinator (humidification–dehumidification cycle) including a compound system consisting of a solar humidifier and subsurface condenser using DoE. *Desalination*, *397*, 9-21.

Paulo, F., & Santos, L. (2017). Design of experiments for microencapsulation applications: A review. *Materials Science and Engineering: C*, *77*(August), 1327-1340.

Puente-Massaguer, E., Lecina, M., & Gòdia, F. (2020). Integrating nanoparticle quantification and statistical design of experiments for efficient HIV-1 virus-like particle production in High Five cells. *Applied Microbiology and Biotechnology*, *104*, 1569-1582. doi: 10.1007/s00253-019-10319-x

Robinson, T. J., Borror, C. M., & Myers, R.H. (2004). Robust parameter design: A review. *Quality and Reliability Engineering International, 20,* 81-101.

Schlueter, A., & Geyer, P. (2018). Linking BIM and Design of Experiments to balance architectural and technical design factors for energy performance. *Automation in Construction*, *86*(February), 33-43.

Setamanit, S. (2018). Evaluation of outsourcing transportation contract using simulation and design of experiment. *Polish Journal of Management Studies*, *18*(2), 300-310.

Sukthomya, W., & Tannock, J. (2005). The optimisation of neural network parameters using Taguchi's design of experiments approach: an application in manufacturing process modelling. *Neural Computing and Applications, 14,* 337-344. doi: 10.1007/s00521-005-0470-3

Tukey, J. W. (1947). Non-parametric estimation II. Statistically equivalent blocks and tolerance regions – the continuous case. *Annals of Mathematical Statistics, 18,* 529-539.

Wald, A. (1943). An extension of Wilks' method for setting tolerance limits. *Annals of Mathematical Statistics, 14,* 45-55.

Wesling, P., & Emamjomeh, A. (1994). T.A.B. Inner-lead bond process characterisation for single point laser bonding. IEEE Transactions on Components Packaging & amp. *Manufacturing Technology Part A, 17*, 142-148.

Yang, G. C. C., & Tsai, C. M. (1998). A study on heavy metal extractability and subsequent recovery by electrolysis for a municipal incinerator fly ash. *Journal of Hazardous Materials, 58,* 103-120.

Yip, H. M., Wang, Z., Navarro-Alarcon, D., Li, P., Cheung, T. H., Greiffenhagen, Ch., & Liu, Y. (2020). A collaborative robotic uterine positioning system for laparoscopic hysterectomy: Design and experiments. *International Journal of Medical Robotics and Computer Assisted Surgery*, *16*(4), e2103. doi: 10.1002/rcs.2103

Yondo, R., Andrés, E., & Valero, E. (2018). A review on design of experiments and surrogate models in aircraft real-time and many-query aerodynamic analyses. *Progress in Aerospace Sciences*, *96*, 23-61. doi: 10.1016/j.paerosci.2017.11.003

Yoo, K. S. (2020). Application of Statistical Design of Experiments in the Field of Chemical Engineering: A Bibliographical Review. *The Korean Society of Industrial and Engineering Chemistry*, *31*(2), 138-146. doi: 10.14478/ACE.2020.1018

Yu, P., Low, M. Y., & Zhou, W. (2018). Design of experiments and regression modelling in food flavour and sensory analysis: A review. *Trends in Food Science & Technology*, *71*(January), 202-215.

Zheng, H., Clausen, M. R., Dalsgaard, T. K., Mortensen, G., & Bertram, H. C. (2013). Time-saving design of experiment protocol for optimisation of LC-MS data processing in metabolomic approaches. *Analytical Chemistry, 85,* 7109-7116.

Volume 13 • Issue 2 • 2021

sciendo

ISMSME International Society for Manufacturing, Service and Management Engineering

received: 1 April 2021
accepted: 10 September 2021

pages: 66-85

Verification of the Job Performance Model based on Employees' Dynamic Capabilities in organisations under the COVID-19 pandemic crisis

Agnieszka Bieńkowska Anna Koszela
Katarzyna Tworek

ABSTRACT
The paper aims to verify the Job Performance Model based on Employees' Dynamic Capabilities (EDC) and explain the mechanisms shaping job performance based on EDC in an initial phase of the crisis in an organisation due to the Black Swan phenomena, on the example of the COVID-19 pandemic of 2020. Empirical research on Italian organisations affected by the crisis shows that the Model is significantly distorted under such conditions. To verify the internal structure of the Job Performance Model based on EDC under critical conditions, the statistical correlation analysis, linear regression analysis and path analysis were executed using SPSS and SPSS AMOS. The research result of the statistical analysis confirmed that the new version of the Model for organisations under the Black Swan phenomenon was statistically significant without work motivation and job satisfaction. It was also proven that P–J fit still linked EDC and job performance through strengthening work engagement. The research confirmed that the Job Performance Model based on EDC, which has so far been verified under normal working conditions, radically changed its structure during the COVID-19 crisis. This means that factors previously considered important in the Job Performance Model based on EDC have become insignificant in shaping job performance. Therefore, this is an inspiration for further research to verify the Job Performance Model based on EDC in different phases of the crisis.

KEY WORDS
employee dynamic capabilities, job performance, management

10.2478/emj-2021-0022

Katarzyna Tworek

Wroclaw University of Science and Technology, Poland
ORCID 0000-0002-6276-2436

Corresponding author
e-mail: katarzyna.tworek@pwr.edu.pl

Agnieszka Bieńkowska

Wroclaw University of Science and Technology, Poland
ORCID 0000-0002-7498-6322

Anna Koszela

Wroclaw University of Science and Technology, Poland
ORCID 0000-0002-3145-4203

Introduction

The management history will remember 2020 as the time when practically every organisation in the world was affected by the extreme crisis caused by the COVID-19 pandemic, having all the characteristics of a so-called Black Swan event (Taleb, 2007; Morales & Andreosso-O'Callaghan, 2020; Murphy et al., 2020). It is a phenomenon of low probability and predictability, causing negative events that are highly consequential and easily explainable but only in ret-

Bieńkowska, A., Koszela, A., & Tworek, K. (2021). Verification of the Job Performance Model based on Employees' Dynamic Capabilities in organisations under the COVID-19 pandemic crisis. *Engineering Management in Production and Services, 13*(3), 66-85. doi: 10.2478/emj-2021-0022

rospect. "Global stock markets appeared to enjoy some level of stability at the start of the year 2020 with positive trends that were disrupted by the emergence of Covid-19" (Morales & Andreosso-O'Callaghan, 2020, p. 2). Such an unpredictable, high-impact event that cannot be prevented causes a crisis in organisations. An internal crisis, especially in its initial phase, forces a necessary reaction by contemporary organisations to ensure their performance, maintain operational continuity and ensure their survival.

It also means that the organisation's goals must be redefined together with operation methods aimed at their achievement. However, decision-makers "are mostly concerned about the cost of mistakes, rather than exact knowledge about the statistical properties" (Taleb, 2007, p. 199). Moreover, no traditional management models and paradigms work under such extreme conditions that cause a crisis in an organisation's functioning (Bieńkowska, Tworek & Zabłocka-Kluczka, 2020); therefore, they need to rely on changed models to secure proper operation under critical conditions. Neither regular organisation's procedures nor the routines and practices are sufficient any longer. They must be verified, redefined and adapted to the extremely critical conditions faced by organisations. More generally, this also means that the existing management paradigms need to be examined and redefined for extremely critical conditions caused by a Black Swan phenomenon to overcome the crisis.

One solution is the Job Performance Model based on Employees' Dynamic Capabilities developed by Bieńkowska and Tworek (2020), which highlights the importance of dynamic human resources capabilities in shaping job performance. The Employees' Dynamic Capabilities (EDC) refer to the concept of Dynamic Capabilities of an organisation proposed by Teece, Pisano and Shuen (1997) and Eisenhardt and Martin (2000), and concern "abilities to integrate, build, and reconfigure employees' competencies to address rapidly changing environment, which is directly influencing the performance of tasks in the workplace" (Bieńkowska & Tworek, 2020, p. 3).

It seems that the verification of the Job Performance Model based on EDC under a crisis caused by a Black Swan event is particularly important due to the nature of dynamic capabilities (here, employees) in the processes of adapting the organisation as a whole to changes in the environment. EDC considers the employee ability to adapt to changes in the environment, their ability to adapt to these changes and creatively solve problems in the organisation. Its role in shaping job performance under a crisis caused by a Black Swan phenomenon has never been analysed, which constitutes a research gap. This explicit research gap is considered in this paper. Hence, the aim is to verify the Job Performance Model based on EDC and explain the mechanisms of shaping job performance in an organisation under crisis caused by a Black Swan phenomenon. The research relates to the initial crisis phase caused by the COVID-19 pandemic in Italy. The impact of EDC on job performance was analysed under the maximum unpredictability, dynamic course, avalanche-like speed of action and extreme intensity conditions. The obtained model was empirically verified using path analysis (sequential mediation) to test how organisations could benefit from EDC achieving job performance under a crisis caused by the COVID-19 pandemic. The verification was based on a sample of organisations operating in Italy during the initial phase of the COVID-19 pandemic. Italy experienced severe consequences of this phase that caused a crisis in a vast majority of organisations. It was the first country in Europe to be hit by the pandemic, and it was impossible to predict its occurrence. Therefore, literature on the early phase of the pandemic often offers such samples (Ghislieri et al., 2021; Molino et al., 2020).

It seems that the Job Performance Model based on EDC — just as other models known from the organisational theory — may exhibit a different structure and behaviour under such conditions (which is in line with the situational theory, important during such an analysis). The acknowledgement of the changes within the Job Performance Model is a crucial contribution to the current management theory. Filling the research gap contributes to theory (verifying the job performance paradigm among organisations undergoing a crisis caused by a Black Swan phenomenon and contributing to the development of crisis–state theory) and practice (proposing mechanisms potentially helping those organisations to survive).

1. Literature overview

Job performance can be defined differently (June & Mahmood, 2011). In general, it refers to a property of the employee behaviour (Sonnentag & Frese, 2002; Motowidlo & Kell, 2012) and is understood as the expected organisational value of what people do (Motowidlo & Kell, 2012). Moreover, job performance concerns both behavioural and outcome

aspects (Sonnentag & Frese, 2002; Griffin et al., 2017); therefore, according to Motowidlo & Kell (2012, p. 93), it is tied "to an individual's behaviour rather than to the results of that behaviour". This paper considers job performance the combination of four aspects: task proficiency, task meticulousness, work discipline and work improvement and readiness for innovation (Ali-Hassan et al., 2015; Kwahk & Park, 2018; Yuen et al., 2018). It includes behaviour and its results. This largely corresponds to the classic approach by Rich et al. (2010), who defined job performance as the aggregated value created for the organisation by the set of employee behaviours directly and indirectly contributing to the fulfilment of organisational goals, expectations and job targets (Campbell, 1990; Borman & Motowidlo, 1993; Rich et al., 2010; June & Mahmood, 2011). The classic performance paradigm (Skinner, 1969) is still valid to some extent, as it offers the main idea regarding various factors influencing job performance and a set of those factors (usually divided into groups, e.g., hygiene factors and motivators (Herzberg, 1987)) constitutes a job performance model. Although the nature and variety of those factors change over the years, various authors of classical and more contemporary literature offer rather similar job performance models featuring various personality traits (Barrick & Mount, 1991; Motowidlo et al., 1997; Salgado, 1997; Tett & Burnett, 2003), work-related attitudes, e.g., work motivation, job satisfaction, employees commitment, work engagement (Hackman & Oldham, 1976; Herzberg, 1987; Judge et al., 2001; Rich et al., 2010) and other so-called alternative predictors (Hunter & Hunter, 1984).

However, a gap in the literature on job performance models was discovered in relation to factors concerning employee abilities to react to changes in the environment. This gave rise to the emergence of so-called adaptive performance (Pulakos et al., 2000; Marques-Quinteiro et al., 2019), aimed at underlining the importance to adapt employee abilities. Such factors became significant since contemporary organisations operate in an increasingly more dynamic environment, which results in the dynamic nature of contemporary work and the workplace. This context required redefining the expectations for modern employees, who are the main organisational resource (Wolf, 2013). Organisations no longer consider employees an existing resource but rather create mechanisms for shaping and using new competences necessary to efficiently perform tasks, flexibly adapting to changes in the environment (Sony & Mekoth, 2016; Marques-Quinteiro et al., 2019). This research gap was addressed by Bieńkowska & Tworek (2020), who developed the concept of Employees' Dynamic Capabilities and used it as a base for a new job performance model.

1.1. Employees' Dynamic Capabilities

Today the organisational environment changes rapidly, at an increasing speed (Pulakos et al., 2000). The literature provides more detail on dynamic capabilities (DC) that define an organisation's ability to integrate, build and reconfigure its internal and external competences to adapt to the rapidly changing environmental conditions (Barton, 1995; Teece et al., 1997). DC are, therefore, a certain strategic process that allows the organisation's resources to be reconfigured in response to the changing market to keep a competitive advantage and adapt to the changes (Handerson & Cockburn, 1994; Teece et al., 1997).

Moreover, the organisational focus on human resources has been a strategic management task in almost every organisation (Gabčanová, 2011). Intellectual capital, human capital and talent as the resources available to employees are becoming increasingly critical to the strategic success of an organisation, determining its competitive advantage (Boudreau & Ramstad, 2017). Human resources and their ability to respond to any signals of changes in the environment are important for ensuring the organisation's operation (Sonnentag & Frese, 2010; Bieńkowska & Tworek, 2020). Such capabilities are referred to in the literature as dynamic employee capabilities, which are defined based on DC definitions by Teece, Pisano and Shuen (Teece & Pisano, 1997). They are understood as the "ability to integrate, build and reconfigure employees' competences to deal with rapidly changing environments that directly affect the performance of tasks in the workplace" (Bieńkowska & Tworek, 2020, p. 3). Therefore, EDC refers to the ability to adapt and solve current problems and keep the long-term improvement of work processes at the workplace. Therefore, EDC is a part of the organisation's DC (Bieńkowska & Tworek, 2020), which has not yet been considered as an influencing factor (Singh & Rao, 2016; Helfat & Martin, 2015; Sotarauta, 2016).

In the above definition, EDC — as a multidimensional notion — refers to employee abilities to:

- be sensitive to changes in the environment (the ability to see changes, recognise opportunities and risks potentially affecting the performance of work),

- adapt to changes in the environment (the ability to undertake preventive actions to avoid problems),
- proactively solve problems in the workplace (if they occur) and include innovations,
- generate innovative ideas and original solutions to problems, and constantly develop competences and qualifications through work (Bieńkowska & Tworek, 2020).

Hence, EDC seems to be especially important for contemporary organisations functioning in a dynamically changing work environment because such conditions induce the dynamic nature of today's work and workplace. Pulakos et al. (2000, p. 612) noticed that nowadays, "workers need to be increasingly adaptable, versatile, and tolerant of uncertainty to operate effectively in this changing and varied environment". Sonnentag and Frese (2002) emphasised that employees should also show the readiness to act and be proactive. At the same time, EDC is the unique combination of employee resources and their ability to flexibly adapt to changes in the environment. This means that EDC also considers the need for continuous personal development and learning (Bieńkowska & Tworek, 2020) as employees must constantly refine and enlarge their skill sets throughout their career (Tews et al., 2011). According to Tews et al. (2011, p. 484), "learning and problem-solving are critical for employee success on the job".

1.2. Job Performance Model based on Employees' Dynamic Capabilities

The role of EDC in shaping employee job performance was confirmed by Bieńkowska and Tworek (2020), which was a basis for developing a mediation Model of Job Performance based on EDC. The pilot study was carried out in 2019 based on 550 organisations operating in Poland and the USA. Based on obtained results, the Job Performance Model based on EDC was verified using organisations operating under normal conditions. Although the model included EDC, it showed that EDC affected job performance and, therefore, was still partly in line with the classic performance paradigm and various versions of classic job performance models localised around work motivation and job satisfaction.

The model included several factors mediating the relation between EDC and job performance, showing that the mechanism of EDC influence on job performance is complex and includes the mediation of the following job-related attitudes and characteristics:

- person–job fit (P–J fit) — understood as a match between individual knowledge, skills and abilities and the job requirements (O'Reilly & Chatman, 1986; Edwards, 1991). It is usually presented as the compatibility between the employee and tasks (including their characteristics) that are expected to be accomplished in exchange for the employment (Kristof, 1996; Chilton et al., 2005),
- work motivation (internal work motivation) — traditionally conceptualised as the degree to which the employee is self-motivated to perform effectively (Hackman & Oldham, 1974),
- job satisfaction — defined as "the degree to which the employee is satisfied and happy with the job" (Hackman & Oldham, 1974, p. 6), or in other words, understood as "a pleasurable or positive emotional state resulting from the appraisal of one's job or job experience" (Rich et al., 2010; Locke, 1976),
- work engagement — understood as the ability of employees to willingly craft themselves to their work roles.

They should "employ and express themselves physically, cognitively, and emotionally during role performances" (Kahn, 1992, p. 694). Engagement is defined as a state of mind related to work, which is described as positive and fulfilling, and an engaged employee is characterised by vigour, dedication, and absorption (Schaufeli & Bakker, 2004, p. 61). Moreover, work engagement is usually understood as the opposite of job burnout (Schaufeli & Bakker, 2004).

The role of each employee in shaping job performance was confirmed to some extent by various literature reports, which, however, did not offer a comprehensive approach to them all. However, based on the obtained empirical results, the Job Performance Model based on EDC included the P–J fit as the first mediator. Next, P–J fit acted as a link between EDC and other factors influencing job performance in the model, such as work motivation, job satisfaction and work engagement. Therefore, the developed model confirmed that the mechanism shaping employee job performance is highly complicated and depends on a set of many factors, but it is justified to include EDC as one of them (Bieńkowska & Tworek, 2020).

1.3. Job Performance and job-related attitudes under a crisis caused by a Black Swan phenomenon

The unexpected Black Swan phenomena that have occurred throughout history have shown that organisations should focus more on developing

adaptability. Organisations that prepare for crisis situations to a certain extent by looking at possible scenarios have a significantly better ability to manage the negative effects of sudden crises (Coutu, 2002). Therefore, to a large extent, there is a conviction that any organisational crisis (caused by an uncommon event) brings negative effects, threatening the survival of an organisation (Coutu, 2002). All crisis events affecting organisations are often turning points in their lives. Unfortunately, analyses conducted by Starbuck et al. (2006) showed that decisions made by managers to prevent the effects of crises had frequently deepened them even further because organisations, e.g., did not implement adequate management plans to develop their ability to continue to operate and survive during and after the crisis (Elliott et al., 2002; Rose & Lim, 2002; Paton, 2009).

If management is not properly prepared for crisis conditions or a Black Swan phenomenon, an organisation is forced to make rapid changes, and some remain unready (Elliott et al., 2002; Rose & Lim, 2002; Paton, 2009). Employees may feel worried, uninterested and unproperly cared for, with growing concern about their job security (Paton, 2009). When the employer does not ensure the safety of the workplace, employees are exposed to stress and negative emotional responses that can affect their work efforts (Jordan et al., 2002; Areni & Chirubolo, 2005). Job insecurity is becoming increasingly inevitable in the current business reality (Sverke & Hellfgre, 2002; Areni & Chirubolo, 2005). Unfortunately, the growing uncertainty of employment raises the dilemma of managing the productivity of employees (Areni & Chirubolo, 2005). Employees can mobilise to work hard to stay in the organisation; however, they can see that all efforts are self-defeating because the organisation makes redundancy decisions (Areni & Chirubolo, 2005). Moreover, employees often experience unfair treatment due to crises in the organisation, which further increases their job insecurity and consequently reduces their productivity (Brockner, 1990; Brockner et al., 1988; Brockner et al., 1992; Parker et al., 1997). On the other hand, the uncertainty of employment forces employees to start looking for a job because of a decreased trust in the organisation, which results in frequent ignorance at work, failure to meet the requirements, i.e., all those behaviours which are observed in the process of withdrawal from work and result in reduced job performance (Chirumbolo & Hellgren, 2003; Davy et al., 1991, Ashford et al., 1989, Lim, 1996; Abramis, 1994; Lim, 1997; Probst, 2002). Based on the above consideration, the following hypothesis can be formulated:

H0: Problems with maintaining business continuity has a negative impact on the job performance of employees.

Problems with ensuring employee job performance under an organisational crisis necessitate solutions that would effectively counteract this phenomenon, threatening the achievement of organisational goals. In this perspective, it seems right to prove the special role of EDC in influencing the employee job performance under crises in the organisation.

The Model of Job Performance based on EDC was verified for a certain continuum of operating conditions under which contemporary organisations function. It features EDC as a factor underlining the need for employees to adapt to changes and shape their job performance. However, it seems that once the conditions become critical, the role of EDC gains even more significance. There is a difference between any conditions caused by even the most turbulent environment and critical conditions induced by the Black Swan phenomena (which are highly unpredictable; thus, organisations cannot prepare for them), which cause an exogenic crisis in the organisation (Nafday, 2009). From the management theory's perspective, the crisis is usually defined as "a low-probability, high-impact event that threatens the viability of the organisation and is characterised by ambiguity of cause, effect, and means of resolution, as well as by a belief that decisions must be made swiftly" (Pearson & Clair, 2008, p. 3). However, an exogenic crisis caused by a Black Swan phenomenon extends much further. A Black Swan event is "the unexpected and unlikely but not an impossible catastrophe that no one ever seems to plan for, the things one does not know or does not know that one does not know" (Nafday, 2009). Such an unpredictable event that goes beyond what is normally expected of a situation and has potentially severe consequences, creating extremely critical operating conditions, which are a source of exogenic crisis in the organisation, is characterised by extremely high turbulence and unpredictability (Pearson & Clair, 2008).

Based on the literature (Durant et al., 2006; Taleb, 2007), many management models (and even paradigms) are no longer valid under such conditions necessitating their reinvention. It seems to be especially true in the case of the job performance paradigm and job performance models based on it. The

focus on appropriate stimulation of employee job performance is important for managers regardless of the organisational operation conditions due to its impact on organisational performance (Sriviboon, 2020). However, job performance becomes an especially crucial issue under extremely critical conditions, which are so dire and unpredictable (caused by a Black Swan phenomenon) that they are causing an exogenic crisis in the organisation and necessitate the reshaping of its operating method. Such conditions can disturb the sustainability of the organisation and even its survival by triggering the escalation of negative phenomena. Moreover, the characteristics of such a crisis are dynamically changing depending on its phase. It seems that the escalation phase is the most unpredictable, turbulent and dangerous. Therefore, retaining and maintaining employee job performance in an escalating crisis requires a different approach and is becoming a necessary condition for organisations to overcome the crisis and restore sustainability and balance (Marques-Quinteiro, 2019; Sahho & Abbas, 2019). The Job Performance Model based on EDC already features a factor stressing the need for employees to adapt to changing conditions. Therefore, it seems to be best-suited as a starting point for describing the mechanism of shaping job performance, especially during the initial phase of a crisis caused by a Black Swan phenomenon (remaining in line with the adaptive performance theory of Pulakos et al., 2000). It seems that mechanisms shaping job performance shown by the model verified for normal conditions would be reshaped in crisis, underlining much further the role of EDC and potentially changing the role of existing factors for organisational survival.

As a set of characteristics helping an employee to quickly integrate, build and reconfigure competencies to meet rapidly changing environmental conditions (Bieńkowska & Tworek, 2020), EDC will become the most expected set of features under crisis caused by a Black Swan phenomenon. Many researchers confirm that employee adaptation to a dynamic environment is key for organisational survival under a crisis. The higher is the level of adaptation, the greater is the complexity of the environment for an organisation to operate successfully (Chakravarthy, 1982; Bharosa & Janssen, 2010). Therefore, organisations with a high level of EDC are much more capable of adapting to changing conditions and employee job performance is more likely to be ensured during a crisis.

The employee sensitivity to changes occurring in the organisation during a crisis and high adaptability to these changes have been recognised as a key factor influencing employee job performance (Fuller et al., 2010; Bieńkowska & Tworek, 2020). Employees with a high level of EDC consider all changes as challenges, and their approach to adapting to these changes is highly proactive (Ployhart & Bliese 2006, Cullen et al., 2014). By adapting to them, employees are ready to take responsibility for the acquisition of the skills that are required by the organisation facing a crisis caused by a Black Swan phenomenon to work again as efficiently (Cullen et al., 2014) as possible for the organisation's success.

Therefore, considering the lack of detailed research on the relationship between EDC and job performance in times of a crisis (especially in its initial phase) caused by a Black Swan phenomenon, complex analysis is necessary and constitutes a part of the research gap considered in this article. Nevertheless, based on the above considerations, a general hypothesis is formulated on the relationship between EDC and job performance in times of crisis:

H1: EDC has a positive impact on job performance during a crisis caused by a Black Swan phenomenon.

The person–job fit (P–J fit) is considered in the literature as a rather complex construct, which generally determines the level of adjustment of employee characteristics to the work they do (Edwards, 1991; Kristof, 1996; Boon & Biron, 2016). Some research studies confirm that employees who are better fitted to their job are more satisfied with it (Caldwell & O'Reilly, 1990; Kristof-Brown et al., 2005; Park et al., 2011; Boon & Biron, 2016) and demonstrate a higher level of job performance (Bieńkowska & Tworek, 2020).

It is worth noting that the P–J fit is also highly susceptible to changes caused by a crisis in the organisation because the P–J fit is composed of two key elements, i.e., the demands–abilities fit, which refers to the degree to which an employee's job requirements are met, and the needs–supplies fit, which refers to the degree to which the individual needs of employees (values, objectives, interests, remuneration, benefit, and competence development) are met by the work they do (Muchinsky & Monahan, 1987; Edwards, 1991; Cable & DeRue, 2002). The changes triggered by a crisis introduce a new order in the organisation, which does not necessarily have to be consistent with the individual

needs of employees. For employees, rapidly changing working conditions during a crisis accumulate a sense of lost control and increased job insecurity, which translates into enormous stress (Theorell et al., 1988; Bolino et al., 2010; Portoghese et al., 2014). Any changes within the organisation (destabilising shocks) force employees from a state of balance (a high P–J fit)to a state of imbalance (Lee & Mitchel, 1994; Chilton et al., 2010). It does not mean that employees will not be able to re-establish their P–J fit balance, but it further underlines the difference in the re-establishing mechanisms (which influence job performance) compared to those used when employees are not forced out of their balance.

Some research informs that employees, who are better fitted for the job, provide organisations with more effective adaptation to changing working conditions (Dunham, 2001; Landsbergis, 2003; Arshadi & Damiri, 2013; Deniz et al., 2015). Even if the P–J fit is disturbed, with proper support, they are able to adapt more quickly to these changes and re-establish the P–J fit balance (Deniz et al., 2015). This allows to formulate the following hypothesis:

H2: The P–J fit has a positive impact on job performance during a crisis caused by a Black Swan phenomenon.

Work motivation is considered one of the main factors strengthening job performance, and this relationship has been known for many years in management (McGregor cited in Ogunna 1999; Azar & Shafighi, 2013; Olusadum & Anulik, 2018). It is also known that during the crisis, work motivation is strongly affected (Mehri et al., 2011) mainly because the organisation's functioning during a crisis is extremely difficult for employees and employers due to a significant impact on the work atmosphere (Závadský et al., 2015). Factors used to motivate employees must be reduced to stopping additional cost generation (Závadský et al., 2015, STATSOFT, 2004). Therefore, managers attempt to introduce motivational factors that require no additional costs (Hitka & Sirotiakova, 2011), such as changing internal communication, developing employees by involving the "tacit" knowledge potential in the organisation or improving processes as a trainer (Hitka & Sirotiakova, 2011), which may further influence the role of motivation for job performance.

Moreover, work motivation tends to naturally decline under such conditions, and it is hard for managers to force it back up again (Závadský et al., 2015). It is hard to motivate employees effectively when they experience increased levels of stress associated with the job-loss fear and inability to perform under changed conditions, which in turn affect their sense of security in the organisation (Závadský et al., 2015). Job insecurity is defined as "perceived powerlessness to maintain desired continuity in a threatened job situation" (Greenhalgh & Rosenblatt, 1984, p. 438). It can be triggered by an exogenic crisis occurring in the organisation (Adkins et al., 2001). Such job insecurity causes a sense of powerlessness and loss of control, which may reduce work motivation (De Spiegelaere, 2014). This conclusion aligns with the much older Active Events Theory, which explains a decline in employee motivation in a crisis-affected organisation because of the impact of negative events that cause negative emotions (Hobfoll, 1989; Weiss & Cropanzano, 1996).

However, research conducted by Mehri et al. (2011) shows that the greatest decrease in work motivation caused by job insecurity is observed among employees who had worked in the organisation before the crisis. Employees who have just started their professional careers during the crisis do not show such a strong decrease in work motivation (Mehri et al., 2011). Nevertheless, work motivation is still an important factor influencing job performance during a crisis.

Job satisfaction most often refers to the degree to which employees like their work (Hackman & Oldham, 1974), i.e., the level of certain positive emotions towards work (Judge, 1994; Hirschfeld, 2000). Dawis (1992) considered that employees felt satisfied with their work when they had the opportunity to make full use of their abilities in the work environment. The organisation enables them to develop abilities and rewards them for effective work (Roberts & Foti, 1998).

Since most crises are hard to predict (especially a Black Swan event), and their duration is usually unknown, there is significant uncertainty about future financial results, and the organisation will keep costs to a minimum to survive in the market (Cao & Chen, 2016). Hence, the organisation undergoing a crisis is usually unable to ensure that all employee expectations are met. "In crisis situations, job satisfaction is likely to drop because of the combined influence of an increase in anxiety and a decrease in individuals' perception of control over the environment" (Spector, 1986, after: Marques-Quinteiro et al., 2019 p. 5). The actions generating additional costs and not necessarily bringing measurable fast benefits to the organisation are limited initially. Therefore, many researchers (Markovits et al., 2014; Cahill et al.,

2015; Green et al., 2016) state that job satisfaction during a recession is distorted. Moreover, a decrease in job satisfaction is caused by negative effects of the recession, which result in a negative assessment of the organisation by employees and, consequently, a decrease in job satisfaction (Markovits, 2014). Based on research conducted during the crisis of 2009, the greatest impact on the reduction of job satisfaction was made by job loss and resignation from promotions (Markovits et al., 2014; Green et al., 2016). The increase in job insecurity as a factor reducing job satisfaction is often mentioned in the literature (Ashford et al., 1989; Sverke & Hellgren, 2002). However, some views suggest that a decline in job satisfaction during a crisis is not so obvious and occurs largely among low-skilled workers, whose job insecurity is very high (Pilipiec et al., 2019). Furthermore, it shows that the effect of crises is not limited to the level of job satisfaction but extends to the relationships of job satisfaction with other factors of the job performance model. The above considerations show that job satisfaction will also be strongly affected by the crisis in the organisation.

A different aspect is the impact of job satisfaction on job performance during a crisis, especially in its initial phase. Although it is more difficult to achieve high levels of employee job satisfaction during a crisis (Spector, 1986), as described above, it is worth taking care of, as there is no reason to reject the statements about the positive impact of job satisfaction on job performance during a crisis. It seems, however, that the sources of employee satisfaction in a crisis are the effects achieved despite the changing conditions in which the organisation functions, at the level of individual employees, teams and the organisation as a whole (Marques-Quinteiro et al., 2019). A sense of community and employee engagement can be triggers of job satisfaction and positively impact job performance.

Employees who work in teams facing difficult conditions feel a stronger social relationship, which often motivates them to continue working (Wessely, 2006; Hüffmeier & Hertel, 2011; Driskell et al., 2018). The meaning of work is yet another important aspect of job satisfaction under difficult conditions (Driskell et al., 2018). The worker who does meaningful work feels much more engaged in it, significantly reducing other stress factors that affect work negatively, such as the sense of job insecurity caused by a crisis (Britt et al., 2016; Driskell et al., 2018). The autonomy of work has a particularly positive impact on the meaning of work (Driskell et al., 2018). It strengthens job satisfaction in the case of employees with highly developed self-leadership (Judge et al., 2001; Keith & Frese, 2005; Marques-Quinteiro et al., 2019). Self-leadership allows employees to evaluate their work more positively, particularly the tasks performed and existing conditions, which consequently may help the employees to look for the positive aspects of the crisis (Neck et al., 1995; Neck & Manz, 2010; Marques-Quinteiro et al., 2019). Due to highly developed self-leadership, employees are able to manage their own work with a high sense of autonomy, which motivates them to work and results in job satisfaction and job performance (Manz, 1986; Breevaart et al., 2015; Marques-Quinteiro et al., 2019). Moreover, it is also important to properly explain the tasks performed by employees. If the crisis brings about some restructuring and employees are obliged to take on new tasks, it is important to explain to them new organisational roles accordingly (Brown & Peterson, 1993; Marques-Quinteiro et al., 2019). All of this is done so that the individual can understand the rationale behind the entrusted responsibilities. This is because it is expected that over time, despite the ongoing crisis, employees will be able to evaluate their work more positively and enjoy it, which will strengthen job performance (Spector, 1986).

Employees engaged in their work are very valuable to the organisation, as engagement, understood as vigour and enthusiasm for work, has a positive impact on their job performance (Bandula et al., 2016).

However, employee work engagement in a crisis is not deterministically decreasing for all employees (Sverke & Hellgren, 2002; Moshoeu & Geldenhuys, 2015) due to a high level of employee identification and individual interpretation of the situation (Moshoeu & Geldenhuys, 2015). Various factors that strengthen engagement (affecting employees negatively and positively) may turbulently and visibly change its role in shaping job performance during various phases of a crisis. The employee reaction to the crisis that can either decrease or increase their work engagement largely depends on their position in the organisation and their work experience (Greenhalgh & Rosenblatt, 1984; De Witt, 1999, 2000). On the one hand, the literature confirms that in the face of a crisis, in which workers feel insecure about their employment and fear losing their job, employees cannot fully engage due to anxiety, anger or frustration (Wiesenfeld et al., 2001; Kiefer, 2005; Mauno et al., 2007; De Spiegelaere, 2014; Wang et al., 2015). On the other hand, Berg, Wrzesniowski & Dutton (2010) argued that job cuts associated with

the crisis might be treated by employees as a challenge that requires them to make a greater effort and perform more efficiently to ensure they stay in the organisation (Lu et al., 2014). Employees may feel that their increased engagement in work, effort and productivity can minimise the possibility of job loss in the face of an economic crisis (Moshoeu & Geldenhuys, 2015). Empirical studies confirm that employees of organisations in a crisis work harder and longer to prove their value to the organisation (Moshoeu & Geldenhuys, 2015; Luthans & Youssef, 2007). Moreover, employees engaged in their work are generally more persistent and proactive in reacting to organisational changes, especially those caused by a crisis (Macey et al., 2008; Bieńkowska & Tworek, 2020). They are willing to look for new and innovative methods of work, take care of development and quickly adapt to any changes in the organisation. Hence, it seems that the decline in work engagement during a crisis is not certain. This work-related attitude may become an especially important element of a job performance model in various phases of a crisis, as it may have the potential to positively influence other elements of the model, not only the job performance itself. Based on the above considerations, the following hypothesis can be formulated:

H3: Work motivation, job satisfaction, and work engagement have a positive impact on job performance during a crisis caused by a Black Swan phenomenon.

1.4. Job Performance Model based on EDC in organisations under a crisis caused by the COVID-19 pandemic

Consequently, the above-mentioned constructs have an impact on employee job performance during a crisis. The Job Performance Model based on EDC proposed by Bieńkowska and Tworek (2020) concerns the EDC's role in shaping job performance and shows the mechanism behind the influence of EDC on job performance. Therefore, it appears logical for the Model to change in a crisis (especially in its initial phase). Usually, a high unpredictability, dynamic course, extreme speed and intensity faced during this crisis phase means that an organisation has significant difficulties planning its activities (Hackman & Oldham, 1974). In this phase, organisations are primarily focused on a flexible and immediate change to their functioning (Pulakos et al., 2000; Cao & Chen, 2016), to ensure the continuity of existence (Cao & Chen, 2016). Unfortunately, in this crisis phase, employees may find it difficult to adapt and take inappropriate actions to prevent losses and achieve results(Sotarauta, 2016).

In such a case, the non-implementation of changes in the organisational operation or continued operation based on "old" procedures, assuming that employee job performance remains unchanged (stiffening/freezing both methods of operation and blocking the redefinition of objectives) frequently results in a counterproductive effect. This means that under a crisis caused by a Black Swan phenomenon, the overriding issue is the change and adaptation of the organisation and its employees to the new operating conditions. Therefore, it seems that the key for achieving the goals of the organisation is the proper use of EDC, adjusting the P–J fit of employees and awakening their engagement in the change process and the achievement of job performance. Hence, it should also be stated that work motivation and job satisfaction are of little importance in this process, although they are essential elements for shaping job performance.

The role of the P–J fit as a mediator of the relationship between EDC and job performance seems to be especially important during a crisis caused by a Black Swan phenomenon. Employees with high levels of EDC (Riemenschneider et al., 2002; Chilton et al., 2010) experience their P–J fit disturbance only for a short period of time, during the transition to a new state of balance or their P–J fit is not disturbed at all. Such employees may treat any changes in the organisation as challenges and an opportunity to improve their knowledge and competences (Zabusky & Barley, 1996). The degree of fulfilment of the needs–supplies fit will be maintained or even increase thanks to dynamic changes occurring during the crisis. This will positively translate into an increase in the P–J fit, influencing job performance even more, being a mediator of its relationship with EDC.

The engagement of employees in their tasks and the process of necessary changes seems to be necessary to reduce the P–J fit deficit by using EDC in the initial phase of the crisis. The efficiency of the adaptation activities undertaken in the organisation and the proper use of the EDC potential in this process depend on whether employees feel engaged. However, it seems that a satisfactory level of work engagement is not that hard to achieve during a crisis. Spurk and Straub (2020) underlined that during a crisis caused by an unpredictable Black Swan phenomenon, employees tended to feel prouder about their ability to continue working and contributing to society,

which strengthened their engagement. Their EDC enables them to work better under such conditions and allows stronger feeling, demonstrating that work engagement translates into job performance during a crisis. Moreover, Risley (2020) stated that with proper inspiration, work engagement supported by adaptability abilities (like EDC) is definitely aimed at ensuring job performance during a crisis, which calls for quick adaptation. The empirical study performed by Song et al. (2020) confirmed that the levels of work engagement raised during a crisis caused by a Black Swan phenomenon, and, surprisingly, it was higher among employees forced to work from home than among those who remain in offices. It shows that work engagement has the potential to build job performance during a crisis, especially when it mediates the relationship between EDC and job performance, strengthening it.

Based on the above considerations, the following hypothesis can be formulated:

H4: EDC influences job performance through the P–J fit and work engagement during a crisis caused by a Black Swan phenomenon.

2. Research methodology

Empirical research based on a survey (using the CAWI method) was conducted to verify the proposed hypothesis and test whether the job performance model based on EDC will change its structure (and internal relations). The sample was selected purposefully and covered organisations operating under critical conditions of the COVID-19 pandemic in Italy (EU) in the early phase of the pandemic. Italy experienced severe consequences of the COVID-19 pandemic, especially at the beginning, as the most surprised country unable to predict the chain of events. There was no time to prepare for possible issues related to everyday functioning, and the crisis hit a vast majority of organisations. The literature on the early phase of the pandemic often uses such samples (Ghislieri et al., 2021; Molino et al., 2020). Therefore, the choice of the country was deliberate, as it was significantly influenced by the COVID-19 pandemic, which during the performed study, caused an escalating crisis in organisations operating in that country. The outbreak of coronavirus SARS-CoV-2 (causing the COVID-19 pandemic) has disrupted the world at the turn of 2019/2020. Before the end of March 2020, it spread globally, hitting all the major economies of the world almost at the same time, which was exceptional. It is an example of a Black Swan phenomenon and, hence, it may be used to verify the hypotheses concerning the changes within the Job Performance Model based on EDC during a crisis caused by such phenomena occurring in an organisation.

The research survey was taken on March 18–22, 2020, few days after the lockdown restrictions were introduced (full lockdown, with the number of COVID-19 cases exceeding 40 000 and the number of deaths from COVID-19 exceeding 4000, and all organisations forced to introduce remote work if possible). Conditions of organisational functioning radically changed, which gave the authors the possibility to test the model under critical conditions that escalated the crisis for most organisations. The characteristics of the sample are presented in Table 1. The sample comprised 115 organisations from Italy. The survey was filled in by managers of the organisations. Several control variables were introduced to confirm the proper diversity of the sample (size and time of operations of the organisation, industry type). Additionally, to make sure that the organisations are meeting the assumption of operating under critical conditions, additional questions concerning the negative influence of the COVID-19 pandemic on their operations were included in the research. All organisations declared an enormous influence of the critical

Tab. 1. Size and time of operation of organisations included in the sample

Organization size	Time of operations				Total
	Less than a year	1 to 5 years	5 to 10 years	More than 10 years	
Micro (below 11 people)	6	5	4	4	19
Small (11–50 people)	4	15	7	1	27
Medium (51–250 people)	1	8	20	7	36
Large (above 250 people)	2	4	14	13	33
Total	13	32	45	25	115

Source: (Bieńkowska et al., 2020).

Tab. 2. Descriptive statistics and reliability of scales of identified variables

No.	Variable	No. of scales	Alpha-Cronbach	M	SD
1	Work motivation	1	--	3.39	0.96
2	Job satisfaction	1	--	3.44	1.01
3	Work engagement	1	--	3.40	0.93
4	P-J fit	1	--	3.57	0.92
5	Job performance	4	0.909	3.39	0.88
6	EDC	4	0.853	3.46	0.74

conditions of the pandemic on all areas of the organisation's operations, including job performance.

2.1. Overview of the variables

The following variables were analysed to verify the model in the crisis escalation phase influenced by critical conditions of organisations functioning during the COVID-19 pandemic:

Work motivation was measured using a 5-point Likert scale, based on a single-item question "Employees in our company are willing and ready to carry out the tasks entrusted to them".

Job satisfaction was measured using a 5-point Likert scale, based on a single-item question "Employees in our company are happy being a member of this company, they do not think about resigning from work".

Work engagement was measured using a 5-point Likert scale, based on a single-item question "Employees in our company are fully engaged in their job at their workplace. They feel bursting with energy and feel strong and vigorous".

The P–J fit was measured using a 5-point Likert scale, based on a single-item question "The knowledge, skills and abilities of employees in our company, fully fit the requirements of their job position. Employees in our company are fully prepared to perform their tasks".

Job performance was measured using a 5-point Likert scale, according to the definition by Campbell (1990) and Borman (1993). The scale contained four items referring to the quality, timeliness, efficiency and effectiveness of the employee tasks at the workplace.

EDC was measured using a 5-point Likert scale, based on four items connected to four dimensions of EDC.

3. Research results

The study was amended by control variables, which were used to verify whether the studied organisations were actually impacted by the COVID-19 pandemic. Questions concerning the negative influence on various aspects of the organisation's operations were asked. In all cases, respondents confirmed that organisations were operating in a crisis caused by the COVID-19 pandemic. Hence, the assumed verification is possible in the chosen sample. To verify the H0 hypothesis and confirm that problems with maintaining business continuity in the organisation (as the confirmation of crisis occurrence) were indeed influencing job performance, the correlation analysis was performed. The analysis showed a correlation between the occurrence and strength of problems with maintaining business continuity significantly influencing job performance ($r= -0.801$, $p < 0.001$). Therefore, the H0 can be accepted, stating that problems with maintaining business continuity have a negative influence on employee job performance.

Next, linear regression analysis was performed to verify hypotheses H2 and H3. The results of the analysis are presented in Table 3. For every independent variable, a separate linear regression model was built. Each of them was statistically significant and showed a cause–effect relationship between an independent and dependent variable. Hence, H2 and H3 hypotheses can be accepted.

The results allowed verifying the internal structure of the Job Performance Model based on EDC under given critical conditions. Hence, as a next step, to verify the H1–Hx hypothesis, the path analysis was executed using SPSS AMOS. Hence, initially, the r-Pearson correlation analysis was performed to establish relationships between analysed variables. The results presented in Table 4 confirm that the correlation was statistically significant and mild or strong in all cases. Based on the results, the place of each variable and the direction of each relationship were established using path analysis. It was established that the model in its original form was defined and significant for the obtained sample, however showing that work motivation ($p = 0.063$) and job satisfaction ($p = 0.162$) had statistically insignificant relationships

Tab. 3. Linear regression analysis of four models using job performance as a dependent variable

Independent variables	Beta	Standard error	P value	R^2	F-Snedecor
EDC	0.453	0.106	0.000	0.198	F(1,109) = 28.085; p < 0.001
P–J fit	0.425	0.085	0.000	0.181	F(1,110) = 24.552; p < 0.001
Work motivation	0.433	0.079	0.000	0.180	F(1,111) = 25.630; p < 0.001
Job satisfaction	0.366	0.080	0.000	0.126	F(1,109) = 17.161; p < 0.001
Work engagement	0.422	0.082	0.000	0.171	F(1,111) = 24.020; p < 0.001

Tab. 4. Correlation weights

		Work motivation	Job satisfaction	Work engagement	P–J fit	EDC
Job satisfaction	r	0.668**	1			
	Sig.	0.000				
	N	113	113			
Work engagement	r	0.641**	0.671**	1		
	Sig.	0.000	0.000			
	N	113	113	113		
P–J fit	r	0.508**	0.653**	0.477**	1	
	Sig.	0.000	0.000	0.000		
	N	113	113	113	113	
EDC	r	0.580**	0.748**	0.587**	0.654**	1
	Sig.	0.001	0.000	0.000	0.000	
	N	113	113	113	113	113
Job performance	r	0.433**	0.483**	0.422**	0.425**	0.451**
	Sig.	0.001	0.000	0.000	0.000	0.000
	N	113	113	113	113	113

Tab. 5. Regression weights

			Estimate	S.E.	C.R.	P
P–J fit	<---	EDC	0.836	0.091	9.183	***
Work engagement	<---	P-J fit	0.496	0.085	5.813	***
Job performance	<---	Work engagement	0.400	0.081	4.939	***

Tab. 6. Standardised total effects

	EDC	P–J fit	Work engagement
P–J fit	0.836	0.000	0.000
Work engagement	0.415	0.496	0.000
Job performance	0.166	0.198	0.421

Tab. 7. Standardised direct effects

	EDC	P–J fit	Work engagement
P–J fit	0.836	0.000	0.000
Work engagement	0.000	0.496	0.000
Job performance	0.000	0.000	0.421

with other elements of the model. Therefore, to obtain a valid model, those variables were removed from the model, which is consistent with the assumptions presented in Chapter 2. The corrected model was verified as defined and well-fitted (Chi2 (3) = 33.123, p <0.001; CFI = 0.779; RMSEA = 0.297). An overview of the changed model is presented in Table 5. Tables 6 and 7 contain the values of total and direct effects occurring among variables within the model. The obtained results allow accepting hypothesis H4. Moreover, the same model and similar results were obtained for every group of organisations included in the sample (the specificity of organisations has not changed the shape of the model).

4. Discussion

The obtained results show differences between the current Job Performance Model based on EDC for organisations operating under a crisis escalation and the model initially obtained by the authors for organisations operating in normal conditions. Although there is a relationship between work motivation, job satisfaction and job performance (verified by linear regression analysis), the influence of work engagement on job performance is much stronger. Its high strength during the crisis caused changes in the structure of the model. Most importantly, according to the obtained sequentially mediated model:

- EDC impacts employee job performance.
- Work motivation is no longer a statistically significant mediator within the model.
- Job satisfaction is no longer a statistically significant mediator within the model.
- The strength of work engagement as a mediator in the model is higher.

The article mainly aimed to examine the structure of the Job Performance Model based on EDC during a crisis in an organisation due to a Black Swan phenomenon, showing changes in the mechanism shaping employee job performance. In particular, the examination focused on the influence of EDC, work motivation, job satisfaction and work engagement on job performance during a crisis. Based on the linear regression analysis and path analysis, the new version of the model was obtained. The Job Performance Model based on EDC modified for the initial crisis phase in an organisation due to a Black Swan phenomenon is presented in Fig. 1.

The obtained results confirmed that during the crisis caused by a Black Swan event, traditional models and paradigms of management no longer worked the same (Bieńkowska, Tworek & Zabłocka - Kluczka, 2020). Due to the predicted disruption of job performance in times of crisis, the Job Performance Model based on EDC was also verified to have a different structure (Fig. 2). As predicted, work motivation and job satisfaction were proven to be no longer relevant elements of the model among organisations experiencing the crisis caused by a Black Swan phenomenon. The new version of the model obtained for organisations operating under the Black Swan phenomenon that affected the world in 2020, i.e., the COVID-19 pandemic, was statistically significant without work motivation and job satisfaction. It was also proven that the P–J fit still provided a link between EDC and job performance through strengthening work engagement.

In this research, the crisis caused by a Black Swan event was only a situational factor in which the model was set. Thus, the focus should not be only on the direct impact of the crisis on work engagement. However, it is not surprising that in the context of a crisis, in many cases, work engagement is stronger. This is an important observation, as in the proposed model, the work engagement continues to be strengthened by the link between EDC and job performance, i.e., the P–J fit. Employees who fit the job better can perform their tasks better. In times of crisis, employees may experience that their P–J fit balance has been disturbed. However, employees better fitted for the job can manage the dynamic changes in the organisation much better (Deniz et al., 2015). As a consequence, EDC-supported employees recover the P–J fit balance much faster, which is affected by the changed conditions of work in the organisation during the crisis triggered by a Black Swan phenomenon.

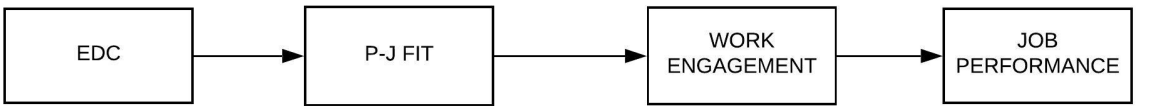

Fig. 1. Shape of the Job Performance Model based on EDC in organisations under a crisis

It is, therefore, important for organisations to be aware of the changes in the basic models shaping employee job performance and to know how to form those factors as they influence organisational performance. Such awareness is crucial for all types of organisations (in case of their size, time of operations etc.), as the mechanism enabling and maintaining employee job performance is changed regardless of their specificity.

Conclusion

The paper aimed to verify the Job Performance Model based on EDC and explain the mechanisms of shaping job performance under a crisis in an organisation due to a Black Swan phenomenon. This issue is particularly relevant in view of the current COVID-19 pandemic, which forced organisations to reshape their operations and employees to adjust to ensure the proper level of job performance.

Employee job performance is a particularly important factor during a crisis, as it determines the level of organisational performance and enables its survival in the market. The research confirmed the mechanism for ensuring job performance through EDC changes during a crisis. Under normal operating conditions, the relationship between EDC and job performance is mediated by the P–J fit, work motivation, job satisfaction and work engagement. The performed empirical research on employee job performance in organisations affected by extreme conditions resulting from the COVID-19 pandemic (an example of a Black Swan phenomenon) demonstrated that work motivation and job satisfaction were no longer significant mediators in the model. However, the P–J fit remained a link between EDC and work engagement in the process of shaping job performance.

Empirical research conducted on Italian organisations affected by the crisis caused by the COVID-19 pandemic shows that all examined work-related attitudes retain their influence on employee job performance, which means that during a crisis, solutions in the field of HRM should strengthen work motivation, job satisfaction and work engagement. At the same time, the attention is drawn by the highest values of the correlation coefficient between EDC and job performance, as well as the R2 coefficient of the regression model for EDC and job performance. This may indicate the critical role of EDC in shaping job performance during such a crisis. At the same time, the Job Performance Model based on EDC changes its shape. It turns out that in the face of a crisis (especially in its initial phase), EDC primarily affects the P–J fit, which is not surprising because the demands–abilities balance gets disturbed. This is a key issue that can be restored thanks to EDC. Then, due to the engagement of employees, the planned job performance can be restored.

Therefore, the paper contributes to the crisis–state theory through initial verification of the job performance paradigm in organisations undergoing a crisis caused by a Black Swan phenomenon. It also offers practical implications as it proposes mechanisms potentially helping organisations to survive through shaping employee job performance under a crisis. It is especially important as a crisis, which is unpredictable, disturbs proper operations and employees are forced to change their working methods. Every mechanism showing organisations how they ensure their proper work seems to be important for them to ensure their continuity.

The obtained results allowed achieving the aim of this article — to verify changes in the Job Performance Model based on EDC occurring in organisations under a crisis caused by a Black Swan phenomenon. However, this research topic is not fully exhausted in the article and has some limitations. The research was conducted in a limited group of organisations operating in Italy, the country among the most affected by the pandemic. However, the obtained results should be treated as a pilot study. This research should be extended to other Black Swan phenomena causing crises in organisations to inform full conclusions on the subject.

Acknowledgments

Supported by grant No. 2020/37/B/HS4/0013123456 of the "National Science Centre in Poland".

Literature

Abramis, D. J. (1994). Relationship of job stressors to job performance: Linear or an inverted-U? *Psychological reports*, *75*(1), 547-558. doi: 10.2466/pr0.1994.75.1.547

Adkins, C. L., Werbel, J. D., & Farh, J. L. (2001). A field study of job insecurity during a financial crisis. *Group & Organization Management*, *26*(4), 463-483. doi: 10.1177/1059601101264004

Ali-Hassan, H., Nevo, D., & Wade, M. (2015). Linking dimensions of social media use to job performance: The role of social capital. *The Journal of Strategic Information Systems*, *24*(2), 65-89. doi: 10.1016/j.jsis.2015.03.001

Areni, A., & Chirumbolo, A. (2005). The influence of job insecurity on job performance and absenteeism: the moderating effects of work attitudes. *SA Journal of Industrial Psychology*, *31*(4), 65-71. doi: 10.4102/sajip.v31i4.213

Arshadi, N., & Damiri, H. (2013). The relationship of job stress with turnover intention and job performance: Moderating role of OBSE. *Procedia-Social and Behavioral Sciences*, *84*, 706-710. doi: 10.1016/j.sbspro.2013.06.631

Ashford, S. J., Lee, C., & Bobko, P. (1989). Content, cause, and consequences of job insecurity: A theory-based measure and substantive test. *Academy of Management Journal*, *32*(4), 803-829. doi: 10.2307/256569

Azar, M., & Shafighi, A. A. (2013), The effect of work motivation on employees' job performance (Case study: employees of Isfahan Islamic Revolution Housing Foundation). *International Journal of Academic Research in Business and Social Sciences*, *3*(9), 432-445. doi: 10.6007/ijarbss/v3-i9/231

Bakker, A. B., Schaufeli, W. B., Leiter, M. P., & Taris, T. W. (2008). Work engagement: An emerging concept in occupational health psychology. *Work & Stress*, *22*(3), 187-200. doi: 10.1080/02678370802393649

Bandula, P. M. K. U., & Jayatilake, L. V. (2016). Impact of employee commitment on job performance: Based on leasing companies in Sri Lanka. *International Journal of Arts and Commerce*, *5*(8), 8-22.

Barrick, M. R., & Mount, M. K. (1991). The big five personality dimensions and job performance: a meta-analysis. *Personnel Psychology*, *44*(1), 1-26. doi: 10.1111/j.1744-6570.1991.tb00688.x

Barton, D. L. (1995). *Wellsprings of knowledge: Building and sustaining the sources of innovation*. Harvard Business School.

Berg, J. M., Wrzesniewski, A., & Dutton, J. E. (2010). Perceiving and responding to challenges in job crafting at different ranks: When proactivity requires adaptivity. *Journal of Organizational Behavior*, *31*(2-3), 158-186. doi: 10.1002/job.645

Bharosa, N., & Janssen, M. (2010). Extracting principles for information management adaptability during crisis response: A dynamic capability view. In *2010 43rd Hawaii International Conference on System Sciences* (pp. 1-10). IEEE. doi: 10.1109/hicss.2010.454

Bieńkowska, A., & Tworek, K. (2020). Job performance model based on Employees' Dynamic Capabilities (EDC). *Sustainability*, *12*(6), 2250. doi: 10.3390/su12062250

Bieńkowska, A., Tworek, K., & Zabłocka-Kluczka, A. (2020). Organizational Reliability Model Verification in the Crisis Escalation Phase Caused by the COVID-19 Pandemic. *Sustainability*, *12*(10), 4318.

Bolino, M. C., Turnley, W. H., Gilstrap, J. B., & Suazo, M. M. (2010). Citizenship under pressure: What's a "good soldier" to do? *Journal of Organizational Behavior*, *31*(6), 835-855. doi: 10.1002/job.635

Boon, C., & Biron, M. (2016). Temporal issues in person–organization fit, person–job fit and turnover: The role of leader–member exchange. *Human Relations*, *69*(12), 2177-2200. doi: 10.1177/0018726716636945

Borman, W. C., & Motowidlo, S. M. (1993). Expanding the criterion domain to include elements of contextual performance,' In N. Schmitt & W. C. Borman (Eds.), *Personnel selection in organizations* (pp. 71-97). San Francisco: Jossey-Bass.

Boudreau, J. W., & Ramstad, P. M. (2007). *Beyond HR: The new science of human capital*. Harvard Business Press. doi: 10.4324/9780203889015.ch2

Breevaart, K., Bakker, A. B., Demerouti, E., & Derks, D. (2016). Who takes the lead? A multi-source diary study on leadership, work engagement, and job performance. *Journal of Organizational Behavior*, *37*(3), 309-325. doi: 10.1002/job.2041

Britt, T. W., Jennings, K. S., Goguen, K., Sytine, A., & Center, J. S. (2016). *The role of meaningful work in astronaut health and performance during long duration space exploration missions*. *NASA/TM-2016-219276*. Houston, Texas: NASA Johnson Space Center.

Brockner, J. (1990). Scope of justice in the workplace: How survivors react to co-worker layoffs. *Journal of Social Issues*, *46*(1), 95-106. doi: 10.1111/j.1540-4560.1990.tb00274.x

Brockner, J., Grover, S. L., & Blonder, M. D. (1988). Predictors of survivors' job involvement following layoffs: A field study. *Journal of Applied Psychology*, *73*(3), 436. doi: 10.1037/0021-9010.73.3.436

Brockner, J., Tyler, T. R., & Cooper-Schneider, R. (1992). The influence of prior commitment to an institution on reactions to perceived unfairness: The higher they are, the harder they fall. *Administrative Science Quarterly*, 241-261. doi: 10.2307/2393223

Brown, S. P., & Peterson, R. A. (1993). Antecedents and consequences of salesperson job satisfaction: Meta-analysis and assessment of causal effects. *Journal of Marketing Research*, *30*(1), 63-77. doi: 10.1177/002224379303000106

Cable, D. M., & DeRue, D. S. (2002). The convergent and discriminant validity of subjective fit perceptions. *Journal of Applied Psychology*, *87*(5), 875. doi: 10.1037/0021-9010.87.5.875

Cahill, K. E., McNamara, T. K., Pitt-Catsouphes, M., & Valcour, M. (2015). Linking shifts in the national economy with changes in job satisfaction, employee engagement and work–life balance. *Journal of Behavioral and Experimental Economics*, *56*, 40-54. doi: 10.1016/j.socec.2015.03.002

Caldwell, D. F., & O'Reilly III, C. A. (1990). Measuring person-job fit with a profile-comparison process. *Journal of Applied Psychology*, *75*(6), 648. doi: 10.1037/0021-9010.75.6.648

Campbell, J. P. (1990). Modeling the performance prediction problem in industrial and organizational psychology. In M. D. Dunnette & L. M. Hough (Eds.), *Handbook of industrial and organizational psychology* (pp. 687-732). Palo Alto, CA: Consulting Psychologists Press.

Campbell, J. P., McCloy, R. A., Oppler, S. H., & Sager, C. E. (1993). A Theory of Performance. In N. Schmitt

& W. C. Borman (Eds.), *Personnel Selection in Organizations* (pp. 35-70). San Francisco: Jossey-Bass Publishers.

Cao, C. X., & Chen, C. (2016). Value of employee satisfaction during the financial crisis. *Managerial Finance, 42*(12), 1208-1225. doi: 10.1108/mf-10-2015-0288

Carmeli, A., & Schaubroeck, J. (2008). Organisational crisis-preparedness: The importance of learning from failures. *Long Range Planning*, *41*(2), 177-196. doi: 10.1016/j.lrp.2008.01.001

Chakravarthy, B. S. (1982). Adaptation: A promising metaphor for strategic management. *Academy of Management Review*, *7*(1), 35-44. doi: 10.5465/amr.1982.4285438

Chilton, M. A., Hardgrave, B. C., & Armstrong, D. J. (2010). Performance and strain levels of it workers engaged in rapidly changing environments: a person-job fit perspective. *ACM SIGMIS Database: the DATABASE for Advances in Information Systems*, *41*(1), 8-35. doi: 10.1145/1719051.1719053

Chirumbolo, A., & Hellgren, J. (2003). Individual and organizational consequences of job insecurity: A European study. *Economic and Industrial Democracy*, *24*(2), 217-240. doi: 10.1177/0143831x03024002004

Coutu, D. L. (2002). How resilience works. *Harvard Business Review, May,* 46-55.

Cullen, K. L., Edwards, B. D., Casper, W. C., & Gue, K. R. (2014). Employees' adaptability and perceptions of change-related uncertainty: Implications for perceived organizational support, job satisfaction, and performance. *Journal of Business and Psychology*, *29*(2), 269-280. doi: 10.1007/s10869-013-9312-y

Davy, J. A., Kinicki, A. J., & Scheck, C. L. (1991). Developing and testing a model of survivor responses to layoffs. *Journal of Vocational Behavior*, *38*(3), 302-317. doi: 10.1016/0001-8791(91)90032-h

Dawis, R.V. (1992). Person-environment fit and job satisfaction. In C. J. Cranny, P. C. Smith & E. F. Stone (Eds.), *Job satisfaction: how people feel about their jobs and how it affects their performance* (pp. 69-88). New York: Lexington Books.

De Spiegelaere, S., Van Gyes, G., De Witte, H., Niesen, W., & Van Hootegem, G. (2014). On the relation of job insecurity, job autonomy, innovative work behaviour and the mediating effect of work engagement. *Creativity and Innovation Management*, *23*(3), 318-330. doi: 10.1111/caim.12079

De Witte, H. (2000). Arbeidsethos en jobonzekerheid: meting en gevolgen voor welzijn, tevredenheid en inzet op het werk. In *Van groep naar gemeenschap. liber amicorum prof. dr. Leo Lagrou* (pp. 325-350). Garant.

De Witte, H. D. (1999). Job insecurity and psychological well-being: Review of the literature and exploration of some unresolved issues. *European Journal of Work and Organizational Psychology*, *8*(2), 155-177. doi: 10.1080/135943299398302

Deniz, N., Noyan, A., & Ertosun, Ö. G. (2015). Linking person-job fit to job stress: The mediating effect of perceived person-organization fit. *Procedia-Social and Behavioral Sciences*, *207*, 369-376. doi: 10.1016/j.sbspro.2015.10.107

Driskell, T., Salas, E., & Driskell, J. E. (2018). Teams in extreme environments: Alterations in team development and teamwork. *Human Resource Management Review*, *28*(4), 434-449. doi: 10.1016/j.hrmr.2017.01.002

Dunham, J. (2001). *Stress in the workplace: Past, present and future*. Wiley.

Durant, R. F., Kramer, R., Perry, J. L., Mesch, D., & Paarlberg, L. (2006). Motivating employees in a new governance era: The performance paradigm revisited. *Public Administration Review*, *66*(4), 505-514. doi: 10.1111/j.1540-6210.2006.00611.x

Edwards, J. R. (1991). Person-job fit: A conceptual integration, literature review, and methodological critique. In C. L. Cooper & I. T. Robertson (Eds.), *International review of industrial and organizational psychology* (pp. 283-357). Oxford, England: John Wiley & Sons.

Eisenhardt, K. M., & Martin, J. A. (2000). Dynamic capabilities: what are they? *Strategic Management Journal*, *21*(10-11), 1105-1121. doi: 10.1002/1097-0266(200010/11)21:10/11<1105::aid-smj133>3.0.co;2-e

Elliott, D., Swartz, E., & Herbane, B. (2010). *Business Continuity Management 2e: A Crisis Management Approach*. Routledge. doi: 10.4324/9780203866337

Fuller Jr, J. B., Hester, K., & Cox, S. S. (2010). Proactive personality and job performance: Exploring job autonomy as a moderator. *Journal of Managerial Issues*, 22(1), 35-51. doi: 10.4337/9781782549352.00009

Gabčanová, I. V. E. T. A. (2011). The employees–the most important asset in the organizations. *Human Resources Management & Ergonomics*, *5*(1), 30-33.

Ghislieri, C., Molino, M., Dolce, V., Sanseverino, D., & Presutti, M. (2021). Work-family conflict during the Covid-19 pandemic: teleworking of administrative and technical staff in healthcare. An Italian study. *La Medicina del lavoro*, *112*(3), 229.

Green, F., Felstead, A., Gallie, D., & Inanc, H. (2016). Job-related well-being through the Great Recession. *Journal of Happiness Studies*, *17*(1), 389-411. doi: 10.1007/s10902-014-9600-x

Greenhalgh, L., & Rosenblatt, Z. (1984). Job insecurity: Toward conceptual clarity. *Academy of Management Review*, *9*(3), 438-448. doi: 10.5465/amr.1984.4279673

Griffin, B., & Hesketh, B. (2003). Adaptable behaviours for successful work and career adjustment. *Australian Journal of Psychology*, *55*(2), 65-73. doi: 10.1080/00049530412331312914

Griffin, M. A., Neal, A., & Parker, S. K. (2007). A new model of work role performance: Positive behavior in uncertain and interdependent contexts. *Academy of Management Journal*, *50*(2), 327-347. doi: 10.5465/amj.2007.24634438

Hackman, J. R., & Oldham, G. (1976). Motivation through the design of work: Test of a theory. *Organizational Behavior and Human Performance*, *16*(2), 250-279. doi: 10.1016/0030-5073(76)90016-7

Hackman, J. R., & Oldham, G. R. (1974). The Job Diagnostic Survey: An instrument for the diagnosis of jobs and the evaluation of job redesign projects. Retrieved from https://files.eric.ed.gov/fulltext/ED099580.pdf

Handerson, R., & Cockburn, I. (1994). Measuring competence. Exploring firm effects in Pharmaceutical Re-

search. *Strategic Management Journal,* 15(S1), 63-84. doi: 10.1002/smj.4250150906

Helfat, C. E., & Martin, J. A. (2015). Dynamic managerial capabilities: Review and assessment of managerial impact on strategic change. *Journal of Management*, *41*(5), 1281-1312. doi: 10.1177/0149206314561301

Herzberg, F. (1987). One more time: how do you motivate employees? *Harvard Business Review*, *65*(5). doi: 10.1007/978-1-349-02701-9_2

Hirschfeld, R. R. (2000). Does revising the intrinsic and extrinsic subscales of the Minnesota Satisfaction Questionnaire short form make a difference? *Educational and Psychological Measurement*, *60*(2), 255-270. doi: 10.1177/00131640021970493

Hitka, M., & Sirotiakova, M. (2011). The impact of economic crisis on the change in motivation of furniture company employees-case study. *Drewno: Prace Naukowe, Doniesienia, Komunikaty*, *54*, 119-126. doi: 10.15388/ekon.2009.0.1058

Hitka, M., & Vacek, V. (2010). *Changes in motivation of workers in production in a production company as a result of the economic crisis. MVK Human Potential Development: Search for Opportunities in the New EU States*. Vilnius, Lithuania: Mykolas Romeris University.

Hobfoll, S. E. (1989). Conservation of resources: A new attempt at conceptualizing stress. *American Psychologist*, *44*(3), 513. doi: 10.1037/0003-066x.44.3.513

Hüffmeier, J., & Hertel, G. (2011). Many cheers make light the work: How social support triggers process gains in teams. *Journal of Managerial Psychology*, *26*(3), 185-204. doi: 10.1108/02683941111112631

Hunter, J. E., & Hunter, R. F. (1984). Validity and utility of alternative predictors of job performance. *Psychological Bulletin*, *96*(1), 72. doi: 10.1037/0033-2909.96.1.72

Jordan, P. J., Ashkanasy, N. M., & Hartel, C. E. (2002). Emotional intelligence as a moderator of emotional and behavioral reactions to job insecurity. *Academy of Management Review*, *27*(3), 361-372. doi: 10.5465/amr.2002.7389905

Judge, T. A. (1994). Job satisfaction: How people feel about their jobs and how it affects their performance. *Administrative Science Quarterly*, *39*(1), 186. doi: 10.2307/2393502

Judge, T. A., Thoresen, C. J., Bono, J. E., & Patton, G. K. (2001). The job satisfaction–job performance relationship: A qualitative and quantitative review. *Psychological Bulletin*, *127*(3), 376. doi: 10.1037/0033-2909.127.3.376

June, S., & Mahmood, R. (2011). The relationship between person-job fit and job performance: A study among the employees of the service sector SMEs in Malaysia. *International Journal of Business, Humanities and Technology*, *1*(2), 95-105. doi: 10.5539/ass.v9n10p114

Kahn, W. A. (1990). Psychological conditions of personal engagement and disengagement at work. *Academy of Management Journal*, *33*, 692-724. doi: 10.5465/256287

Keith, N., & Frese, M. (2005). Self-regulation in error management training: emotion control and metacognition as mediators of performance effects. *Journal of Applied Psychology*, *90*(4), 677. doi: 10.1037/0021-9010.90.4.677

Kiefer, T. (2005). Feeling bad: Antecedents and consequences of negative emotions in ongoing change. *Journal of Organizational Behavior: The International Journal of Industrial, Occupational and Organizational Psychology and Behavior*, *26*(8), 875-897. doi: 10.1002/job.339

Kristof, A. L. (1996). Person-organization fit: An integrative review of its conceptualizations, measurement, and implications. *Personnel Psychology*, *49*(1), 1-49. doi: 10.1111/j.1744-6570.1996.tb01790.x

Kristof-Brown, A. L., Zimmerman, R. D., & Johnson, E. C. (2005). Consequences of individuals'fit at work: a meta-analysis of person–job, person–organization, person–group, and person–supervisor fit. *Personnel Psychology*, *58*(2), 281-342. doi: 10.1111/j.1744-6570.2005.00672.x

Kwahk, K. Y., & Park, D. H. (2018). Leveraging your knowledge to my performance: The impact of transactive memory capability on job performance in a social media environment. *Computers in Human Behavior*, *80*, 314-330. doi: 10.1016/j.chb.2017.10.047

Landsbergis, P. A. (2003). The changing organization of work and the safety and health of working people: a commentary. *Journal of Occupational and Environmental Medicine*, *45*(1), 61-72. doi: 10.1097/00043764-200301000-00014

Lee, T. W., & Mitchell, T. R. (1994). An alternative approach: The unfolding model of voluntary employee turnover. *Academy of Management Review*, *19*(1), 51-89. doi: 10.5465/amr.1994.9410122008

Lim, V. K. (1996). Job insecurity and its outcomes: Moderating effects of work-based and nonwork-based social support. *Human Relations*, *49*(2), 171-194. doi: 10.1177/001872679604900203

Lim, V. K. (1997). Moderating effects of work-based support on the relationship between job insecurity and its consequences. *Work & Stress*, *11*(3), 251-266. doi: 10.1080/02678379708256839

Lu, C. Q., Wang, H. J., Lu, J. J., Du, D. Y., & Bakker, A. B. (2014). Does work engagement increase person–job fit? The role of job crafting and job insecurity. *Journal of Vocational Behavior*, *84*(2), 142-152. doi: 10.1016/j.jvb.2013.12.004

Luthans, F., & Youssef, C. M. (2007). Emerging positive organizational behavior. *Journal of Management*, *33*(3), 321-349. doi: 10.1177/0149206307300814

Macey W., & Schneider, B. (2008). The meaning of employee engagement. *Industrial and Organizational Psychology*, *1*, 3-30. doi: 10.1111/j.1754-9434.2007.0002.x

Manz, C. C. (1986). Self-leadership: Toward an expanded theory of self-influence processes in organizations. *Academy of Management Review*, *11*(3), 585-600.

Markovits, Y., Boer, D., & van Dick, R. (2014). Economic crisis and the employee: The effects of economic crisis on employee job satisfaction, commitment, and self-regulation. *European Management Journal*, *32*(3), 413-422. doi: 10.1016/j.emj.2013.09.005

Marques-Quinteiro, P., Vargas, R., Eifler, N., & Curral, L. (2019). Employee adaptive performance and job satisfaction during organizational crisis: the

role of self-leadership. *European Journal of Work and Organizational Psychology*, *28*(1), 85-100. doi: 10.1080/1359432x.2018.1551882

Mauno, S., Kinnunen, U., & Ruokolainen, M. (2007). Job demands and resources as antecedents of work engagement: A longitudinal study. *Journal of Vocational Behavior*, *70*(1), 149-171. doi: 10.1016/j.jvb.2006.09.002

Mehri, M., Iqbal, M. J., Hekmat, R. K., & Ishaq, H. M. (2011). Impact of global financial crises on job security and job motivation of employees of banking sector in Iran. In *2nd International Conference on Business and Economic Research. Malaysia (proceedings)*.

Molino, M., Ingusci, E., Signore, F., Manuti, A., Giancaspro, M. L., Russo, V., Zito, M., & Cortese, C. G. (2020). Wellbeing costs of technology use during Covid-19 remote working: An investigation using the Italian translation of the technostress creators scale. *Sustainability*, *12*(15), 5911.

Morales, L., & Andreosso-O'Callaghan, B. (2020). Covid19: Global Stock Markets "Black Swan". *Critical Letters in Economics & Finance*, *1*, 1-14. doi: 10.1016/j.asieco.2012.09.002

Moshoeu, A. N., & Geldenhuys, D. J. (2015). Job insecurity, organisational commitment and work engagement among staff in an open distance learning institution. *Southern African Business Review*, *19*(1), 22-43. doi: 10.25159/1998-8125/5832

Motowidlo, S. J., & Kell, H. J. (2012). Job performance. *Handbook of Psychology, Second Edition*, *12*. doi: 10.1002/9781118133880.hop212005

Muchinsky, P. M., & Monahan, C. J. (1987). What is person-environment congruence? Supplementary versus complementary models of fit. *Journal of Vocational Behavior*, *31*(3), 268-277. doi: 10.1016/0001-8791(87)90043-1

Murphy, J. F., Jones, J., & Conner, J. (2020). The COVID-19 pandemic: Is it a "Black Swan"? Some risk management challenges in common with chemical process safety. *Process Safety Progress*, *39*(2), e12160. doi: 10.1002/prs.12160

Nafday, A. M. (2009). Strategies for managing the consequences of black swan events. *Leadership and Management in Engineering*, *9*(4), 191-197. doi: 10.1061/(asce)lm.1943-5630.0000036

Neck, C. P., & Manz, C. C. (2010). *Mastering self-leadership: Empowering yourself for personal excellence*. Pearson.

Neck, C. P., Stewart, G. L., & Manz, C. C. (1995). Thought self-leadership as a framework for enhancing the performance of performance appraisers. *The Journal of Applied Behavioral Science*, *31*(3), 278-302. doi: 10.1177/0021886395313004

Ogunna, A. E. C. (1999). *Public administration in Nigeria: Theory and practice*. Owerri: Great Versatile Publishers Ltd.

Olusadum, N. J., & Anulika, N. J. (2018). Impact of motivation on employee performance: A study of Alvan Ikoku Federal College of Education. *Journal of Management and Strategy*, *9*(1), 53-65. doi: 10.5430/jms.v9n1p53

O'Reilly, C. A., & Chatman, J. (1986). Organizational commitment and psychological attachment: The effects of compliance, identification, and internalization on prosocial behavior. *Journal of Applied Psychology*, *71*(3), 492. doi: 10.1037/0021-9010.71.3.492

Park, H. I., Monnot, M. J., Jacob, A. C., & Wagner, S. H. (2011). Moderators of the relationship between person-job fit and subjective well-being among Asian employees. *International Journal of Stress Management*, *18*(1), 67. doi: 10.1037/a0021854

Parker, S. K., Wall, T. D., & Jackson, P. R. (1997). "That's not my job": Developing flexible employee work orientations. *Academy of Management Journal*, *40*(4), 899-929. doi: 10.5465/256952

Paton, D. (2009). Business continuity during and after disaster: building resilience through continuity planning and management. *ASBM Journal of Management*, *2*(2), 1. doi: 10.1201/ebk1439819029-p8

Pearson, C. M., & Clair, J. A. (2008). Reframing Crisis Management. *Crisis Management*, *11*, 1-24. doi: 10.2307/259099

Pilipiec, P., Groot, W., & Pavlova, M. (2019). A Longitudinal Analysis of Job Satisfaction During a Recession in the Netherlands. *Social Indicators Research*, 1-31. doi: 10.1007/s11205-019-02233-6

Ployhart, R. E., & Bliese, P. D. (2006). Individual adaptability (I-ADAPT) theory: Conceptualizing the antecedents, consequences, and measurement of individual differences in adaptability. In *Understanding adaptability: A prerequisite for effective performance within complex environments*. Emerald Group Publishing Limited. doi: 10.1016/s1479-3601(05)06001-7

Portoghese, I., Galletta, M., Coppola, R. C., Finco, G., & Campagna, M. (2014). Burnout and workload among health care workers: the moderating role of job control. *Safety and Health at Work*, *5*(3), 152-157. doi: 10.1016/j.shaw.2014.05.004

Probst, T. M. (2002). Layoffs and trade-offs: Production, quality, and safety demands under the threat of job loss. *Journal of Occupational Health Psychology*, *7*(3), 211. doi: 10.1037/1076-8998.7.3.211

Pulakos, E. D., Arad, S., Donovan, M. A., & Plamondon, K. E. (2000). Adaptability in the workplace: Development of a taxonomy of adaptive performance. *Journal of Applied Psychology*, *85*(4), 612. doi: 10.1037/0021-9010.85.4.612

Rich, B. L., Lepine, J. A., & Crawford, E. R. (2010). Job engagement: Antecedents and effects on job performance. *Academy of Management Journal*, *53*(3), 617-635. doi: 10.5465/amj.2010.51468988

Riemenschneider, C. K., Hardgrave, B. C., & Davis, F. D. (2002). Explaining software developer acceptance of methodologies: a comparison of five theoretical models. *IEEE transactions on Software Engineering*, *28*(12), 1135-1145. doi: 10.1109/tse.2002.1158287

Risley, C. (2020). Maintaining Performance and Employee Engagement During the COVID-19 Pandemic. *Journal of Library Administration*, *60*(6), 653-659. doi: 10.1080/01930826.2020.1773716

Roberts, H. E., & Foti, R. J. (1998). Evaluating the interaction between self-leadership and work structure in predicting job satisfaction. *Journal of Business and Psychology*, *12*(3), 257-267. doi: 10.1023/a:1025067128193

Rose, A., & Lim, D. (2002). Business interruption losses from natural hazards: conceptual and methodological issues in the case of the Northridge earthquake. *Global Environmental Change Part B: Environmental Hazards*, *4*(1), 1-14. doi: 10.3763/ehaz.2002.0401

Sahho, A. P. D. N. M., & Abbas, O. A. (2019). The impact of the organizational crisis on the level of job performance/An exploratory study of the opinions of a sample of divisions managers at University of Samarra. *Tikrit Journal of Administration and Economics Sciences*, *15*(Special Issue), 78-87.

Salgado, J. F. (1997). The five factor model of personality and job performance in the European community. *Journal of Applied Psychology*, *82*(1), 30. doi: 10.1037/0021-9010.82.1.30

Schaufeli, W. B., & Bakker, A. (2004). *Work Engagement Utrecht Scale, Preliminary Manual. Version 1.1, December*. Utrecht: Occupational Health Psychology Unit Utrecht University. doi: 10.1037/t05561-000

Singh, B., & Rao, M. K. (2016). Effect of intellectual capital on dynamic capabilities. *Journal of Organizational Change Management*, *29*(2), 129-149. doi: 10.1108/jocm-12-2014-0225

Singh, N. (2004). Flexibility in product development for success in dynamic market environment. *Global Journal of Flexible Systems Management, 5*(1), 1-13.

Skinner, W. (1969). Manufacturing-missing link in corporate strategy. *Harvard Business Review.* doi: 10.2307/257791

Skowron-Mielnik, B. (2009). Efektywność pracy próba uporządkowania pojęcia [Work efficiency. An attempt at ordering the concept]. *Zarządzanie Zasobami Ludzkimi*, *1*, 31-44. doi: 10.33141/po.1997.06.06

Smith, P. C., Kendall, L. M., & Hulin, C. L. (1969). *Measurement of satisfaction in work and retirement*. Chicago, IL: Rand McNally.

Song, L., Wang, Y., Li, Z., Yang, Y., & Li, H. (2020). Mental Health and Work Attitudes among People Resuming Work during the COVID-19 Pandemic: A Cross-Sectional Study in China. *International Journal of Environmental Research and Public Health*, *17*(14), 5059.

Sonnentag, S., & Frese, M. (2002). Performance concepts and performance theory. *Psychological Management of Individual Performance*, *23*(1), 3-25. doi: 10.1002/0470013419.ch1

Sony, M., & Mekoth, N. (2016). The relationship between emotional intelligence, frontline employee adaptability, job satisfaction and job performance. *Journal of Retailing and Consumer Services*, *30*, 20-32. doi: 10.1016/j.jretconser.2015.12.003

Sotarauta, M. (2016). Shared leadership and dynamic capabilities in regional development. In *Regionalism contested* (pp. 63-82). Routledge.

Spector, P. E. (1986). Perceived control by employees: A meta-analysis of studies concerning autonomy and participation at work. *Human Relations*, *39*, 1005-1016.

Spurk, D., & Straub, C. (2020). Flexible employment relationships and careers in times of the COVID-19 pandemic. *Journal of Vocational Behavior*, *119*, 103435. doi: 10.1016/j.jvb.2020.103435

Sriviboon, C. (2020). Impact of selected factors on job performance of employees in it sector: A case study of Indonesia. *Journal of Security & Sustainability Issues*, *9*(1), 28-41. doi: 10.9770/jssi.2020.9.j(3)

Starbuck, C. M., Berrens, R. P., & McKee, M. (2006). Simulating changes in forest recreation demand and associated economic impacts due to fire and fuels management activities. *Forest Policy and Economics*, *8*(1), 52-66. doi: 10.1016/j.forpol.2004.05.004

STATSOFT. (2004). STATISTICA (data analysis software system), version 7. Retrieved from www.statsoft. com

Sverke, M., Hellgren, J., & Näswall, K. (2002). No security: a meta-analysis and review of job insecurity and its consequences. *Journal of Occupational Health Psychology*, *7*(3), 242. doi: 10.1037/1076-8998.7.3.242

Taleb, N. N. (2007). Black swans and the domains of statistics. *The American Statistician*, *61*(3), 198-200. doi: 10.1198/000313007x219996

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal*, *18*(7), 509-533. doi: 10.1002/(sici)1097-0266(199708)18:7<509::aid-smj882>3.0.co;2-z

Tett, R. P., & Burnett, D. D. (2003). A personality trait-based interactionist model of job performance. *Journal of Applied Psychology*, *88*(3), 500. doi: 10.1037/0021-9010.88.3.500

Tews, M. J., Michel, J. W., & Noe, R. A. (2011). Beyond objectivity: The performance impact of the perceived ability to learn and solve problems. *Journal of Vocational Behavior*, *79*(2), 484-495. doi: 10.1016/j.jvb.2010.11.005

Theorell, T., Perski, A., Åkerstedt, T., Sigala, F., Ahlberg-Hultén, G., Svensson, J., & Eneroth, P. (1988). Changes in job strain in relation to changes in physiological state: a longitudinal study. *Scandinavian Journal of Work, Environment & Health*, 189-196. doi: 10.5271/sjweh.1932

Tworek, K., Bieńkowska, A., & Zabłocka-Kluczka, A. (2020). *Organizational Reliability: Human Resources, Information Technology and Management*. Routledge. doi: 10.4324/9781003047995

Vander Elst, T., Van den Broeck, A., De Witte, H., & De Cuyper, N. (2012). The mediating role of frustration of psychological needs in the relationship between job insecurity and work-related well-being. *Work & Stress*, *26*(3), 252-271. doi: 10.1080/02678373.2012.703900

Wang, H. J., Lu, C. Q., & Siu, O. L. (2015). Job insecurity and job performance: The moderating role of organizational justice and the mediating role of work engagement. *Journal of Applied Psychology*, *100*(4), 1249. doi: 10.1037/a0038330

Weiss, H. M., & Cropanzano, R. (1996). Affective Events Theory: A theoretical discussion of the structure, causes and consequences of affective experiences at work. In B. M. Staw & L. L. Cummings (Eds.), *Research in organizational behavior: An annual series of analytical essays and critical reviews* (pp. 1-74). Elsevier Science/JAI Press.

Wessely, S. (2006). Twentieth-century theories on combat motivation and breakdown. *Journal of Contemporary History*, *41*(2), 268-286.

Wiesenfeld, B. M., Brockner, J., Petzall, B., Wolf, R., & Bailey,

J. (2001). Stress and coping among layoff survivors: A self-affirmation analysis. *Anxiety, Stress and Coping*, *14*(1), 15-34. doi: 10.1080/10615800108248346

Wolf, J. (2013). Improving the sustainable development of firms: the role of employees. *Business Strategy and the Environment*, *22*(2), 92-108. doi: 10.1002/bse.1731

Yuen, K. F., Thai, V. V., Wong, Y. D., & Wang, X. (2018). Interaction impacts of corporate social responsibility and service quality on shipping firms' performance. *Transportation Research Part A: Policy and Practice*, *113*, 397-409. doi: 10.1016/j.tra.2018.04.008

Zabusky, S. E., & Barley, S. R. (1996). Redefining success: Ethnographic observations on the careers of technicians. In P. Osterman (Ed.), *Broken Ladders: Managerial Careers in Transition* (pp. 185-214). Oxford University Press.

Závadský, J., Hitka, M., & Potkány, M. (2015). Changes of employee motivation of Slovak enterprises due to global economic crisis. *E a M: Ekonomie a Management*, *18*(1), 57-66. doi: 10.15240/tul/001/2015-1-005

Volume 13 • Issue 2 • 2021

sciendo

ISMSME International Society for Manufacturing, Service and Management Engineering

received: 1 March 2021
accepted: 31 August 2021

pages: 86-98

Impact of the COVID-19 pandemic on logistics firms and their resilience: case studies in Thailand

Sun Ketudat Chawalit Jeenanunta

ABSTRACT

The novel Coronavirus (COVID-19) is an infectious disease that is currently causing challenges and opportunities in all sectors worldwide. The logistic industry plays an enormous role in keeping the countries functional, and it accounts for 13.4 % of the total GDP in Thailand. This article aims to identify and justify critical success factors for the Logistic Industries experiencing success and failure during the pandemic. The research was conducted using semi-structured interviews with top managers of three companies from March to September 2021, which is phase 4 of the pandemic. The findings we analysed using thematic analysis to understand the critical factors within the industry. Logistics companies of different sizes were selected for this purpose as case studies aimed to identify the resemblance of the effects and find the relationship with company resilience. Five key supporting factors were identified for the logistics firms to be resilient during the pandemic, including flexibility, Business Continuity Plan, market diversification, IT systems, and leadership.

KEY WORDS

COVID-19, logistics industry, business continuity plan, thematic analysis, Thailand, resilient, cross-comparison

10.2478/emj-2021-0023

Chawalit Jeenanunta

Thammasat University, Thailand
ORCID 0000-0002-1932-9776

Corresponding author:
e-mail: chawalit@siit.tu.ac.th

Sun Ketudat

Thammasat University, Thailand
ORCID 0000-0002-1563-4845

Introduction

The novel Coronavirus (COVID-19) is an infectious disease currently terrorising the world. It was first officially reported in the City of Wuhan, China, in December 2019. The pandemic affected everyone, leading to a crisis in all industries around the globe. Businesses are forced to adapt and adjust to the "new normal" to survive in the new world with the COVID-19.

Ketudat, S., & Jeenanunta, Ch. (2021). Impact of the COVID-19 pandemic on logistics firms and their resilience: case studies in Thailand. *Engineering Management in Production and Services, 13*(3), 86-98. doi: 10.2478/emj-2021-0023

From January 2020 to September 2021, Thailand had approx. 1 200 000 confirmed cases of COVID-19, with roughly around 12 000 deaths. The number of infections has increased throughout each phase, with the highest number of 22 000 new cases on a single day. Thailand had implemented a lockdown policy for the population's safety to decrease or prevent the spread of the infection.

To understand resilience under the COVID-19 pandemic, challenges faced by industries must be identified and analysed in terms of time and the scope of influence, resulting in business interruptions and bottlenecks. Extreme uncertainty can be caused, e.g., by political instability, pandemic, terrorism, natural disasters, and a financial meltdown. Challenges differ by scope and duration; thus, resilience scenarios also vary depending on challenges. Another aspect for consideration is the internal business and industry challenges faced by managers, such as increased workload, the second shift in the form of domestic work and home-schooling, employee loyalty in the home office, extended availability outside working hours, tight timing and high density as well as content-rich online meetings, and widespread changes. Business resilience is achieved by preparing for strange events. Coping with the pandemic requires prevention and protection, adaptability and reactivity to challenges, and the ability to recover with greater strength after the pandemic.

This paper analyses the effects caused by the COVID-19 pandemic on the logistics industry in Thailand to identify positive and negative aspects and understand the resilience of companies operating in the field. The data was collected from three different logistics companies. The study was conducted using a semi-structured interview and thematic analysis (Braun & Clarke, 2006) to derive a theme for the resilience key factors (Scharte et al., 2014). The three selected companies represent the logistics industry in Thailand. Respondents represented the top management of the companies. The research paper aspired to find the overall effect throughout the four pandemic phases from the beginning of 2020 up to September 2021.

In addition to the effect of the COVID-19 pandemic, the paper also focused on the "new normal", i.e., the lifestyle policies implemented on-site and off-site in each company. The first COVID-19 case in Thailand was reported in January 2020. The number of cases drastically increased in the first phase between March to May 2020 due to the lack of awareness of the new virus. As a result, the government was forced to act and implement a lockdown policy, closing schools, nightclubs, and other public places. Closed airports and travel restrictions made employees switch to working from home. Additionally, the government placed a curfew for 22.00–04.00 hrs. As the number of infections decreased, the government lifted the lockdown regulation. Thailand's citizens experienced too much stress due to working from home or unemployment. Phase 2 started in January to March 2021; the number of infections surged as a new cluster emerged from the Myanmar labour in Samut Sakhon. The government returned to the restriction policies forbidding migrant workers to travel to provinces with high infection levels in Samut Sakhon, Chonburi, Rayong, Chantaburi, and Trad. Phase 3 began in April 2021 with an infection cluster from clubs in Thonglor, resulting in the return to the lockdown policies. Furthermore, phase 4 and the most recent lockdown started in July, with COVID-19 spreading throughout all provinces.

1. Literature review

Researchers have investigated the impact of the pandemic and business resilience in other industries using various organisational concepts. E.g., delivery and takeaway services have a strong positive effect on the business resilience of the restaurant and bar industry (Neise et al., 2021). The COVID-19 impact is significant for the airline industry, which saw a massive drop in stocks and the market. Possible policies are suggested to help industries cope with the pandemic and recover after the crisis (Maneenop & Kotcharin, 2020).

Businesses that implemented a well-prepared Business Continuity Plan as a strategic management counter to the COVID-19 pandemic are likely to be more efficient in terms of survivability and recovery (Margherita & Heikkilä, 2021).

Resilience is the ability of businesses to quickly respond, react, and adapt to a downfall. Businesses that overcome a downfall make improvements related to internal and external factors. Different factors contribute to the resilience during the pandemic, such as the workforce, social, environmental, operational, commercial, financial aspects and future resilience. Examples of internal factors are the workforce, operational and financial aspects, and future resilience. Workforce resilience plays a massive role as an internal factor; thus, protective and preventive measures are crucial during the pandemic. Staff is

a vital business asset in managing the workflow. Operational and future resilience are internal factors that impact continuous value generation and require to implement risk management and operational plans during the pandemic and later. Financial resilience is an internal factor related to the management of cash flows and the business value to identify possible performance improvements and loss cuts. Social, environmental, and commercial resilience are examples of external factors (Al-Ayed, 2019). Social and environmental resilience can influence the business positively. The resilience cycle consists of preparation, prevention, protection, response, and recovery (Scharte et al., 2014). Shin and Park found that leadership is a significant factor in the firm's resilience during disruptive events (Shin & Park, 2021). Wang and Chen found that diversification and flexibility enhance the firm's efficiency (Wang & Chen, 2021).

2. Research methods

The research was qualitative and used semi-structured interviews for thematic analysis as a deductive approach. The aim was to identify the pandemic effects on the logistics companies in Thailand. The semi-structured questions were formulated by the authors. The thematic analysis was applied, using six steps: familiarise the data set, initial codes, generate codes, validity and reliability of the themes, define and name the themes, and interpret and report.

This research aimed to find positive and negative effects faced by the logistics industry in Thailand during the 4 phases of the COVID-19 pandemic. The semi-structured interview asked questions regarding the company's background, the status before and during the 4 phases of the COVID-19 pandemic, and the

Tab. 1. Characteristics of case studies

Company Characteristics	Case A	Case B	Case C
Established	2018	1988	1989
Size	Small	Midsize	Large
Number of staff	15	92 in Thailand 280+ (Total)	700+staff in Thailand 100+ outsource 22,000+ staff (Total)
Number of offices	1	6 in Thailand 80 partners globally	500
Covered region	Global	Global, but focuses mainly on South-East Asia	Global
Focused Region	International Market	Local Market	International Market
Services provided	sea & air freight, customs clearance, warehousing and distribution services etc.	sea & air freight, truck inland transportation, customs clearance, warehousing and distribution services etc.	total supply chain solution freight & logistic services (air, sea, road, warehousing & distribution, supply chain solutions, systems & technologies), industry solutions (automotive, chemicals, consumer goods, defence & government, energy & petrochemicals etc.)
Specialised product of transportation	Specialises in food, food packaging (dry & frozen), automotive, & medical equipment	Specialises in general cargo (automobile-parts, machinery, home & furniture, canned food, tech gadgets, etc.), perishable (Thai agricultural products – seasonal fruits), project cargo (oversized cargo both air & sea)	Specialises in transporting; high-tech electronics, industrial, and life-science products (pharmaceutical)

response to the pandemic, such as the actions taken, risk management, and Business Continuity Plans.

The research participants were top managers of three different logistics companies of different sizes, which were selected hoping to find the resemblance and patterns of the COVID-19 effects.

3. Research results

The selected companies were used as a case study to show challenges, opportunities, and the main overall effect within each phase of the COVID-19 pandemic. For Case A, B, and C, the participants of the semi-structured interview held positions of Managing Director, Business Development Executive, and Managing Director, respectively. The characteristics of the participants are summarised in Table 1. The research provided a sufficient amount of data for thematic analysis and finding the key resilience factors during the pandemic.

3.1. Case A

Case A is a new logistics company established in 2018 with more than 15 staff members. Covering logistics globally, it specialises in the transport of goods between Thailand and the United States, targeting international markets. The company specialises in the transport of food, food packaging for dry and frozen products, automotive and medical equipment, and some other niche goods.

The company provides sea and air freight services. Approx. 65 % of its business is sea freight, and the rest — air freight. Other services include the customs clearance, warehousing, and distribution. The company owns only one office, which is the headquarters located in the central district of Ekamai. It is known as a small logistics company acting as a freight forwarder, arranging shipments from suppliers to customers for individuals and corporations. A freight forwarder acts as an agent contacting other logistics providers to carry out shipments using different modes of transport via sea, air, rail, and land.

The company faced several challenges during the pandemic. Many people could not get to work. Employees and customers of the company had to work from home, which meant they lacked the usual access to their resources, causing delays and cancellations in production. The company was affected by the loss of continuous orders that were expected before the COVID-19 pandemic.

Nevertheless, some opportunities were created as well. Due to the lockdown, which was especially noted in the UK, people experienced boredom and tiredness, which resulted in the use of e-commerce. A surge was registered in the demand for products from Asia and especially Thailand.

From October 2020, in the hype of the COVID-19 pandemic, the demand was so high that shipping line vessels for cargo transportation were overwhelmed and fully booked. However, a crisis was expected in July 2020. Shipping companies panicked and pulled large vessels out, aiming to cut predicted losses. However, the surged demand skyrocketed cargo prices. The sudden lack of equipment and space provided the logistics industries with an enormous opportunity, and the price has increased 10-fold since October 2020.

With people spending more and limited capacity and space, company A substantially advanced in the logistics industry. As the company had space allocation and supply contracts, a sudden massive booking of shipments came through. The available capacity helped the company make a massive income.

New customers from different countries and industries became interested in the company for supply for logistics services. For a small company with limited competitive power, things have turned around. It stumbled upon opportunities that were never available before.

To respond to the COVID-19 pandemic, the company implemented risk management measures, such as telecommunications for conducting businesses, social distancing, working from home, wearing masks, regular use of alcohol gel and spray, and temperature checks before and after work. The company plans to expand, using the opportunities given by the pandemic.

3.2. Case B

Case B is a mid-size company established in 1988, with 92 staff members, six offices worldwide, and the headquarter located in the Bangna district, which is a suburban area of Bangkok City. The company provides logistics services worldwide but focuses more on Southeast Asia with over 80 partners globally. Company B is a freight forwarder that offers a one-stop-shop service for multimodal logistics, sea and air freight, truck-inland and cross-border transportation, customs clearance and consultancy, warehousing and distribution services, special projects and site logistics. The company specialises in the

logistics of general cargo, perishable products, and project cargo management. The general cargo consists of automobile parts, machinery, home and furniture, canned food, tech gadgets etc. Perishable products are mostly Thai agricultural produce (e.g., seasonal fruits), and project cargo management relates to the transportation of oversized cargo via air and sea.

Before the COVID-19 situation, the company experienced an increase in the transportation of e-commerce products (i.e., tech gadgets) and tried to obtain new accounts as more SMEs imported products from China and other countries. Some opportunities were created before the pandemic as the Thai government invested more in the infrastructure, which attracted more investments, such as the EEC project and more free trade agreements. However, the attempt to acquire new accounts faced difficulties due to pricing and competition.

As a result of the COVID-19 pandemic, imports and exports remained the same as before the pandemic. However, the total volume of imports and exports has decreased significantly. An increase was registered in the volume of food and medical products; however, a decrease was experienced in the volume of clothing and home decoration products.

The company faced similar challenges as in the previous case, i.e., employees having to work from home, cancelled orders and production, dropped orders from regular contractors, more prolonged bottlenecks within the delivery process, difficulties in booking and getting space, and container imbalance for customers, which may result in a loss of customers. Opportunities were created in the form of growing e-commerce shipments due to the rise of online platforms globally. Since there was a shortage of containers, new export and import companies became interested in company B for space and bookings.

In response to the pandemic, company B implemented safety procedures for staff, asking 50 % of them to work from home and others to come into the office once every week or two. Also, customer visits were limited to only those inevitable and, upon advance permission, refraining as much as possible from outside visitors. Transportation services were provided for staff members to be dropped off and picked up from their houses to their workplaces. The company moved their counter services to a warehouse for releasing the Bill of Lading (B/L) and Delivery Order (D/O). The staff was requested to wear masks and regularly use alcohol gel. Employees having a temperature higher than 37.5 °C were transferred to the hospital, staff members were asked to wear masks in public places, all business trips were deferred until further notice, and private employee trips or annual leaves were to be agreed upon in advance with the management. Also, offices were regularly deep cleaned and disinfected. For company B, the overall effect was mostly negative, but the business is slowly recovering.

3.3. Case C

Company C was established in 1989 and is considered a large global logistics business. It provides a total supply chain solution and has more competitive power compared to other players in the logistics industry. Company C has been acquired and taken over many times over the years. It has over 700 regular staff members in Thailand and more than 100 outsourced. In total, it has over 22 000 staff members and more than 500 offices worldwide. The company provides a total supply chain solution of freight and logistics services, such as transportation via air, sea and land, warehousing and distribution, supply chain solutions, and systems and technologies. The company also offers industry solutions in the automotive, chemicals, consumer goods, defence and government, energy and petrochemicals sectors etc. Company C focuses on international trade and transport of specialised goods, such as high-tech electronics (82 %), industrial (12 %) and life-sciences products (5 %), such as pharmaceuticals and other (1 %).

Freight is primarily transported via air and sea. The rail network is underdeveloped in Thailand. The country had plans to connect the railway system to Laos and China, but they had to be postponed due to the COVID-19 pandemic.

Before the pandemic, airlines prioritised their services for passengers, which roughly amounted to 70–80 % of their business, with the rest representing cargo and other services.

In terms of air freight in 2019, Thailand focused on export, which roughly amounted to 1 400 000 tons and the annual revenue of THB 3 000 – 4 000 million. In April 2020, the airline stopped operating due to the COVID-19 pandemic, which caused a vast disruption in transportation. The volume dropped by 35 % by the end of 2020. Airfreight exported 900 000 tons and doubled the revenue to THB 7000 million.

During the national lockdown, the airline was forced to temporarily shut down. This posed a massive challenge for logistics companies offering air freight as airlines had to cancel flights for passengers.

In over 30 years of experience as the managing director, this was the first time when flights only carried cargo and no passengers. The pandemic caused some technical difficulties with the weight balance since aircrafts had cargo underneath and no passengers. This issue had to be resolved.

Usually, a wide-body or large aircraft can hold roughly an average of 200 passengers of 100 kg per person, which is equivalent to 20 tons. In addition, it can hold up to 5 – 30 tons of cargo. A narrow-body or small aircraft has a maximum weight limit of 1 or 2 tons. Once the technical difficulty with the weight imbalance was resolved, a wide-body aircraft held up to 50 – 56 tons. The cost for logistics using air freight has been very high.

Company C has faced more challenges compared to the previous two cases due to its size and more direct challenges caused by the pandemic, namely, putting air freight on hold, weight balancing, and decreased volumes. Other challenges were related to employees working from home, cancellation of orders, a more prolonged bottleneck at the delivery process, the shortage of labour and cargo. Some staff members stopped working due to the fear of getting infected.

On the other hand, the company experienced an enormous benefit from the COVID-19 pandemic. Due to a significant increase in e-commerce and sudden shortages, the company saw a 200 – 400% increase in revenue. Air-charters were more frequent, customers used different freight services, and the willingness-to-pay increased. The company had the competitive power to set the price for the customers.

The volume of imported and exported products decreased because of the panic among the on-site and the off-site workers, fearing the pandemic. This resulted in a sudden labour shortage. On the other hand, the company's revenues spiked up from the sudden shortage of services and a surge in demand, causing the prices to increase drastically. The willingness-to-pay increased because of the need to transport fresh products and the high customer demand.

To ensure risk management, the company had a Business Continuity Plan for such situations as the pandemic. The plan aimed to keep the workflow continuous. Aiming to ensure safety, on-site and off-site staff were given laptops with private VPNs to conduct work from home. On-site employees operated in shifts as Team A and Team B, rotating once every week to ensure appropriate social distancing. Also, the company rented a VPN server for conducting business from home. All staff members had to wear masks, observe social distancing, use alcohol disinfectant, wash hands etc. Also, infected members of staff had to stay in isolation and follow a set of rules set out in the BCP. Telecommunication for business meetings and online learning for new staff members were used as well.

Looking at all four phases of the COVID-19 pandemic, phase one (beginning of 2020) posed a challenge in terms of decreased volume. Phase two (the second half of 2020) saw a slow recovery from the volume loss. In the later phases of the pandemic to September 2021, the volume and the revenue exceeded the loss.

This case study helped to identify key factors leading to successful resilience during the pandemic, i.e., flexibility and speed at which a company can adapt and overcome obstacles. Also, business safety can be ensured with a Business Continuity Plan guiding the company towards well-being, diversified market within the logistics companies, advanced IT systems, and appropriate leadership decisions and strategies.

4. Thematic analysis

This research section aimed to identify characteristics, the resemblance and dissimilarity between cases to find the case study's theme. For this purpose, cross-case analysis and thematic analysis were used. The results of the theme were based on key processes of the resilience cycle. The five key action stages (Scharte et al., 2014) consist of preparation, prevention, protection, response, and recovery.

The first stage for the five key processes of the resilience cycle starts with preparation; at this stage, firms begin to be aware of the pandemic and prepare for the potential situation to be faced shortly. A Business Continuity Plan or specific actions taken to cope with the pandemic are examples of the preparation stage. The second stage is the prevention of the virus from spreading to the inner circle of the company and reducing risk factors. The third key factor is protection. At this stage, companies have to ensure their safety from any negative impacts to come. The fourth stage is responding, i.e., companies taking action against the pandemic, such as implementing policies for working from home, social distancing and following the Business Continuity Plan to endure the workflow, health and safety of each individual. The last stage is recovery, at which companies had learned and finally adapted to coping with the situation of the pandemic and prepared for another possible pandemic in the future.

Fig. 1. Resilience Cycle

Source: (Scharte et al., 2014).

Tab. 2. Thematic Analysis for the processes of the resilience cycle

Descriptive of the transcript					
Resilience	Theme	Code	Case A	Case B	Case C
2. Prevention; 3. Protection	New Normal	Work-From-Home	Company A had very few changes because it was new and used a more advanced system in the offices. The work-from-home policy may have created small challenges due to the change in the working environment. Respondents said that the work–life balance might have been disturbed due to working from home and the lockdown. Now, people have to learn to live their lives under the "new normal" conditions and adapt to change.	Company B implemented a policy for having half of their office staff working from home and rotating every two weeks as a safety precaution ensuring social distancing. Business meetings were conducted from home via Zoom and Google Meet. Staff members had to adapt their homes to become their workspace following the criteria given by the company. As the company is local and a traditional type of workplace, having to do the work from department to department manually, it posed a challenge.	Company C ensured the health and safety of their staff by implementing the policy for working from home. Company C implemented its own Business Continuity Plan to maintain the workflow. Based on the BCP, employees were provided with work laptops with a VPN to the database. Company C used WebEx to conduct international meetings and Zoom and Google Meet for regular local meetings with office staff. Telecommunication solutions were also used to recruit new staff and for online learning.
2. Prevention; 3. Protection; 5. Recovery	New Normal	Telecommunication	WebEx, Zoom, Google Meet, and other means of telecommunication were used more regularly for conducting the business. Before the COVID-19 pandemic, new customers were contacted and signed physically, but under the circumstances, business meetings were conducted online.	The company continued working traditionally; the adaption and adoption of more telecommunication solutions was a struggle.	The company rented a private VPN server to work within its system based on the recommendation from the Business Continuity Plan. International business was conducted through telecommunications.

1. Preparation; 2. Prevention; 3. Protection	New Normal	People's behaviour	As a result of the lockdown, customers became more interested in e-commerce for online shopping, creating a vast demand.	People tend to buy things, and since no money could be spent on trips, vacations or shopping, the focus fell on e-commerce. The COVID-19 pandemic causes the fear of the virus spreading to loved ones, so people feel they have to self-isolate and spend money online.	The lockdown encouraged customers to spend their money on goods and services from abroad, leading to a huge advantage to the logistics industry.
4. Response; 5. Recovery	Effect of the COVID-19 pandemic	Opportunities	For a small business, the situation took an unexpected turn and created an opportunity that otherwise might not have ever emerged, i.e., new customers signing contracts for services. Moreover, due to the lockdown, e-commerce skyrocketed, resulting in increased revenue. For case A, the positive impact from the COVID-19 pandemic was so high that they could overlook the adverse effect. The company signed contracts before the COVID-19 pandemic for essential goods and products, i.e., food and pharmaceutical equipment; these products played a key role in the success of the company.	A growing number of customers was searching for logistics companies for import and export once the capacity of other logistics companies was exceeded or the prices were too high. Stocks for logistics companies rapidly increased due to the high service demand.	The large company was ready for significant events as it had made advance plans for dealing with the pandemic as it already had experienced many events, such as natural disasters (volcano eruption, floods etc.). This created an advantage over other industry players. The demand for logistics was high, giving the company and the overall logistics industry a high increase in revenue (doubling its annual revenue). The large size and competitive power in the industry provided the company with an enormous advantage over other players.
1. Preparation	Effect of the COVID-19 pandemic	Challenges	Companies in other industries, such as clothing, had to lay off staff or shut down due to the negative impact of the pandemic. People were unable to get out of their homes and live their regular lives, shopping and going on trips. Some companies within the logistics industry could not handle the negative impact within the first phase of the pandemic and were forced to shut down or stay on hold. Initially, conducting the business and adapting to the changes working from home was a bit of a challenge. However, once the company learned to live under the "new normal" conditions, the workflow increased productivity.	The adaptation to working from home was difficult for the company as it was more traditional in terms of working style. Cancellation of orders and production was a challenge due to the pandemic; the company suppliers had their difficulties and caused delays or order cancellations. Regular contractors expected orders to be dropped. Another issue was a more prolonged bottleneck within the delivery process. Difficulties with bookings and space for customers could have led to the loss of customers and a decrease in volume.	Working from home was implemented for staff members on-site and off-site, causing some delays in the delivery process in terms of a bottleneck. Customers cancelled orders to save their businesses. As a total supply chain solution provider, the company had to look in detail into every business process for logistics. One issue was the weight imbalance for cargo due to no passengers on aircrafts. Due to labour and cargo shortage, the volume decreased by 35 %.

1. Preparation; 4. Response; 5. Recovery	Effect of the COVID-19 pandemic	Phases	During phase 1 of the COVID-19 pandemic in Thailand, several complications emerged in the adjustment and adaptation to the new way of living. The panic in other industries resulted in a decrease in volume and revenue. However, in the later phases (2 and 3), after the adjustment, the effect became positive due to the sudden lack of equipment and space shortage. The demand surged, causing a rise in revenue. During phase 4, there were several complications with bookings and the capacity for customers as the market is very competitive.	The company found it difficult to adjust during the first two phases. However, once the policies were fully adapted and adopted and plans were adjusted to the pandemic, the company started slowly recovering from the loss accumulated in the previous phases.	As the company had a Business Continuity Plan set beforehand, it could continue working with slight difficulties by adapting the policies. Once the company was fully adjusted, the stocks and the revenue escalated rapidly. The company had the competitive power to set the prices for the customers as the demand grew due to the sudden service shortage.
4. Response; 5. Recovery	Post-COVID-19	Reaction to Sudden Change	Shipping lines expected a massive crisis from the pandemic, causing a panic and pulling large vessels out for saving the capacity and the cost of holding the vessels; however, the prediction made by the shipping lines was wrong. The demand surged from the pandemic, causing a shortage in equipment, labour, and shipping capacity. No one had expected a rapid increase in demand. Investors worldwide became interested in the logistics industries and bought stocks.	People feared the virus, and no one wanted to spread it to their loved ones. There was a sudden labour shortage, which caused a huge disruption. People stayed home and spent most of their money on e-commerce which positively affected the logistics companies.	For the first time in over 30 years of the logistics industry, aircrafts only transported cargo without any passengers.
1. Preparation	Post-COVID-19	Survive	Some other logistics companies had to pause their activities or even shut down at the start of the pandemic. One factor for the shutdown could have been the lack of need for the transported goods during the crisis, leading to a tremendous loss. Luckily for company A, it transported necessary goods, such as food and pharmaceutical equipment. The respondent observed that the food industry always survives during crises as it is an essential part of our lives.	Social distancing, working from home, telecommunication solutions, and disinfection are necessary for the safety of staff and maintenance of the company's workflow. They are the top priority. The company believes it may recover faster than the loss was acquired in the first stages of the pandemic.	The company had experience with other serious events, such as natural disasters, so it knew how to cope with situations like the COVID-19 pandemic. The company specialises in electrical products, which are essential for everyone, especially at times like these, such as laptops or PCs for working from home.
4. Response; 5. Recovery	Post-COVID-19	Recovery or Resilience	Once required adaptations were made, logistics companies started slowly recovering from losses experiences in the first phases of the COVID-19 pandemic in Thailand.	The company has overcome the challenges faced in the first two phases and is slowly recovering.	As there were many losses in the volume, the company gained more revenue from the pandemic.

5. Discussion and cross-case analysis

All three cases have shown the resilience plans of preparation, prevention, protection, response, and recovery. All three companies had a Business Continuity Plan in advance to prevent the spread of the virus within the company and protected themselves by following plans and policies regarding their safety. Furthermore, all three cases showed signs of making a quick recovery. Some cases may differ slightly and lag on the recovery due to the pandemic.

Tab. 3. Cross-case comparison

Case analysis factor	Case A	Case B	Case C
Interviewee's management position	Managing Director	Business Development Executive	Managing Director
Level of education	Bachelor	Masters	Highschool
Years in the experience of logistic industry	20	10	36
Covered region	Global	Global, but focuses mainly in South-East Asia	Global
Office headquarter location	Ekamai Centre of Bangkok	Bangna Suburb of Bangkok	Lat Krabang Suburb of Bangkok
Communication channel	Telecommunication video conference	Telecommunication video conference	Telecommunication video conference
Effect from Phase 1	Negative	Negative	Negative
Effect from Phase 2	Positive	Negative	Positive
Effect from Phase 3	Positive	Positive	Positive
Effect from Phase 4	Negative	Positive	Positive
Overall Effect of COVID-19	Positive	Negative	Positive
Opportunities	E-commerce, more customers, increased demand etc.	E-commerce, more customers, increased demand; increased price charged, growth in e-commerce shipments from online platforms etc.	Increased e-commerce, increased revenue by 200 –400 % due to a sudden shortage, air-charter, customers using different freight, increased willingness-to-pay, competitive power etc.
Challenges	Working from home, cancellation of orders and production, regular contractors expecting orders dropped etc.	Working from home, cancellation of orders and production, regular contractors expecting orders dropped, a lengthier bottleneck within the delivery process, harder to book and get space for customers, which might lead to loss of a customer etc.	Working from home, some cancellation of orders, weight-balance for air cargo, volume decreased by 35 %, shortage in labour & cargo, a lengthier bottleneck within the delivery process etc.
Actions are taken in response to the COVID-19	Working from home, using more telecommunications etc.	Working from home, rotating employees in each department, sending original billing documents by postal service and less visits by bike messengers, allocation of service counter to segregate external visitors to a specific larger area to reduce crowding and promote digitalisation of work (telecommunication) etc.	Rotating divisions for work from home, promoting greater digitalisation, using telecommunications as a means for conducting businesses and ensuring the business workflow, providing laptops with VPN access to the company's system.

Case analysis factor	Case A	Case B	Case C
Risk Management	Social distancing, working from home, wearing masks, using alcohol gel/spray regularly etc.	50/50 working from home policy with rotation and limited customers visitation, refraining as much as possible from outside visitors. Provided transportation services for employees from home to office (and vice versa). Company B relocated their counter service to the warehouse for releasing B/L and D/O. Staff had to wear masks while working and use alcohol gel, with a temperature check-up policy. Transferring employees with a temperature higher than 37.5 °C to the hospital. Postponing all business travel until further notice. Prior agreement required from the management before private trips or annual leave; offices regularly deep cleaned and disinfected etc.	Implementation of the Business Continuity Plan (BCP), working from home policies. The company provided employees with laptops and separated them into Teams A and B for weekly shifts (on-site staff) to prevent crowding (ensure social distancing); VPN (rented the VPN server for conducting work from home); wearing masks, social distancing, alcohol disinfectant, washing hands etc.
Future Plans	Plans for Expansion	Expansion branch (a new office located at Suvarnabhumi Airport)	TBA

The resilience of companies was impacted during the four phases of the pandemic. During the first phases, the outcome of the pandemic for the logistics industry was negative. Sudden changes were made to adapt to the situation to ensure adaptation and survivability. The pandemic is difficult for companies with low flexibility and having to implement such changes as an online platform to be used for working from home or generate plans to be used during the pandemic. The readiness and flexibility of a company result in adaptiveness and a positive impact.

Within the first phase of the COVID-19 pandemic, companies in the logistics industry faced a loss of customers, shortage of labour and equipment, cancellation of orders and production, and a decrease in the volume of import and export, resulting in decreased total revenue. The overall theme for the first phase was a negative impact.

In the second phase of the COVID-19 pandemic, two-thirds of studied companies demonstrated quick resilience and experienced a positive impact. The positive impacts resulted from companies being flexible. Business Continuity Plans helped to protect the companies from pandemic outcomes. Also, e-commerce was used more frequently by customers as a result of the lockdown, which had a positive impact on the companies. Due to the high demand for logistics, revenue began to multiply.

In the third and fourth phases of the pandemic, the logistics companies recovered and experienced positive effects with businesses improving.

Based on the thematic analysis and cross-case comparison, the following factors were identified as necessary for the logistics firms to be resilient during the pandemic.

The flexibility in the workplace adaptation, so work could continue during the lockdown or implemented special procedures for safety. A company with great flexibility will have a more positive impact than a company with low flexibility. Creating or adopting a Business Continuity Plan played a massive role in business resilience during the pandemic.

A Business Continuity Plan is a programme of means for the prevention and protection of the business resulting in its resilience. To better use or improve the Business Continuity Plan, the company needs to assess it through regular reviews and identify threats clearly to prepare good solutions. The plan must be followed up with an analysis of the pandemic effects for certain areas of the business, making sure that the plan is accessible and tested regularly. As the case study demonstrated, companies that implement a Business Continuity Plan recover faster than companies that have no plan or lag behind with its drafting.

A positive impact can be achieved by diversifying products provided to the customer, e.g., essential prod-

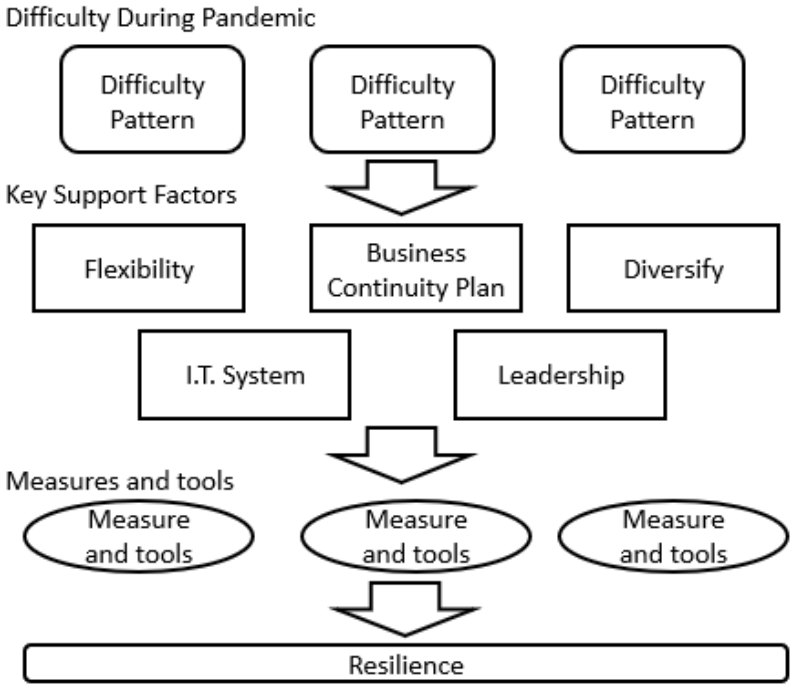

Fig. 2. Identification of key supporting factors for resilience of logistics firms

ucts (food), electrical equipment (for online learning and working from home), pharmaceutical equipment etc. By diversifying the market, companies can average out the risk of negative impacts with the positive impacts to improve growth or further develop the business.

IT systems play a critical role in resilience for coping with the pandemic. Advanced systems tend to have a more positive impact than less up-to-date systems. Adjusting the company's workflow with the help of IT systems ensures continuous business operation.

Moreover, the last key success factor for the company's resilience is leadership knowing how to strategically manage the company in times of crisis. Leadership is among the most important aspects of the company's stability during the pandemic. Supervision helps the company advance through struggles following a strategic plan for operational and financial business management.

Conclusion

COVID-19 has been a massive disruption in all industries, causing many companies to shut down. However, in the midst of the negativity, some positive effects were discovered. The logistics industry was among the few that survived and improved due to the pandemic. Even though some challenges were faced initially, companies that managed to survive the first phase of the pandemic will see a positive effect.

This research paper looked at the impact of the COVID-19 pandemic on the logistics industry and its resilience. The thematic analysis research was based on a semi-structured interview of three companies in the Thai logistic industry and their activities from the beginning of March 2020 to September 2021, covering four phases of the COVID-19 pandemic in Thailand. The semi-structured interview was recorded for transcription to be used for further analysis. Thematic analysis was the selected deductive approach for distinguishing the codes and generating the themes for this research, using resilience key factors as guidance for the interviewed questions.

The research identified key factors that resulted in the resilience of logistics firms during the pandemic: flexibility, Business Continuity Plan, diversified market, IT systems, and leadership. These factors should be confirmed in a further study by empirical evidence, such as Analytic Hierarchy Process (AHP) and multiple regression.

Other companies in logistics industries are advised to implement a Business Continuity Plan. It helps the company to be prepared for crises. Companies that have a Business Continuity Plan tend to move towards a positive effect and show strong recovery from the pandemic. Additionally, the plan helps to prepare for the later stage of the post-pandemic.

Acknowledgements

The authors would like to thank the participants from the three companies for allowing to conduct the case study for the research. This research is fully supported by the Center of Excellence in Logistics and Supply Chain Systems Engineering and Technology (COE LogEn), Sirindhorn International Institute of Technology Thammasat University.

The publication of the article for 11th International Conference on Engineering, Project, and Production Management - EPPM2021 was financed in the framework of the contract no. DNK/SN/465770/2020 by the Ministry of Science and Higher Education within the "Excellent Science" programme.

Literature

Al-Ayed, S. I. (2019). The impact of strategic human resource management on organizational resilience: an empirical study on hospitals. *Business: Theory and Practice*, *20*, 179-186. doi: 10.3846/btp.2019.17

Amankwah-Amoah, J. (2021). COVID-19 pandemic and innovation activities in the global airline industry: A review. *Environment International*, *156*, 106719.

Asano, T., & Nagayama, A. (2021). Analysis of workload required for removal of drifting pumice after a volcanic disaster as an aspect of a port business continuity plan: A case study of Kagoshima Port, Japan. *Journal of Disaster Risk Reduction*, *64*, 102511.

Aviv-Sharon, E., & Aharoni, A. (2020). Generalized logistic growth modeling of the COVID-19 pandemic in Asia. *Infectious Disease Modelling*, *5*, 502-509. doi: 10.1016/j.idm.2020.07.003

Barman, A., Das, R., & Kanti De, P. (2021). Impact of COVID-19 in food supply chain: Disruptions and recovery strategy. *Current Research in Behavioral Sciences*, *2*, 100017.

Ivanov, D. (2020). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transportation Research Part E: Logistics and Transportation Review*, *136*, 101922.

Li, Z., Zhou, Q., Chen, M., & Liu, Q. (2021). The impact of COVID-19 on industry-related characteristics and risk contagion. *Finance Research Letters*, *39*, 101931.

Malavika, B., Marimuthu, S., Joy, M., Nadaraj, A., Asirvatham, E. S., & Jeyaseelan, L. (2021). Forecasting COVID-19 epidemic in India and high incidence states using SIR and logistic growth models. *Clinical Epidemiology and Global Health*, *9*, 26-33. doi: 10.1016/j.cegh.2020.06.006

Maneenop, S., & Kotcharin, S. (2020). The impacts of COVID-19 on the global airline industry: An event study approach. *Journal of Air Transport Management*, *89*, 101920.

Scharte, B., Hiller, D., Lerismann, T., & Thoma, K. (2014). Introduction. In K. Thoma (Ed.), *Resilien-Tech "Resilience by Design": a strategy for the technology issues of the future* (pp. 9-17). München, Germany: Herbert Utz Verlag.

Sharma, G. D., Thomas, A., & Paul, J. (2021). Reviving tourism industry post-COVID-19: A resilience-based framework. *Tourism Management Perspectives*, *37*, 100786.

Spieske, A., & Birkel, H. (2021). Improving supply chain resilience through industry 4.0: A systematic literature review under the impressions of the COVID-19 pandemic. *Computers & Industrial Engineering*, *158*, 107452.

Thoma, K., Scharte, B., Hiller, D., & Leismann, T. (2016). Resilience Engineering as Part of Security Research: Definitions, Concepts and Science Approaches. *European Journal for Security Research*, *1*, 3-19. doi: 10.1007/s41125-016-0002-4

Wang, H., Lo, Y., Liu, Y., Qing, F., Zhou, Y., Chen, Y., & Fang, D. (2021). Study on the Influencing factors of urban economic resilience in post epidemic Era – A case study of Kunming City. *Journal of Urban Management*, *10*, 255-264.

Wang, Y.-C., & Chen, T. (2021). A Bi-objective AHP-MIN-LP-GA approach for Flexible Alternative Supplier Selection amid the COVID-19 pandemic. *Soft Computing Letters*, *3*, 100016.

Wen, W., Yang, S., Zhou, P., & Gao, S. Z. (2021). Impacts of COVID-19 on the electric vehicle industry: Evidence from China. *Renewable and Sustainable Energy Reviews*, *144*, 111024.

sciendo

ISMSME International Society for Manufacturing, Service and Management Engineering

received: 15 March 2021
accepted: 31 August 2021

pages: 99-113

Resilient manufacturing: case studies in Thai automotive industries during the COVID-19 pandemic

Najavadh Kaeo-tad Chawalit Jeenanunta
Kwanchanok Chumnumporn
Thanapatra Nitisahakul Vararat Sanprasert

ABSTRACT

The coronavirus pandemic is a crisis that disrupts the global supply chain and slows down the world economy. A significant challenge for the companies in the manufacturing sector is to mitigate risks related to the COVID-19 outbreak. Grounded in the resilience theory, resilience (i.e., prepare, prevent, protect, respond, and recover processes) aims to manage risks and ensure business continuity. This research aims to identify the key factors for the resilient manufacturing management of Thai automotive industries during the COVID-19 outbreak. Three outstanding companies of tier 1 automotive suppliers have been selected as case studies in this work. This qualitative research was completed by using a semi-structured interview. The target interviewers were CEOs or general managers. The data analysis was divided into two phases. Phase one summarised the interview data of each company. Phase two used thematic analysis and cross-case analysis to identify resilience practices' patterns, themes, and multi-factors. The findings indicate three key factors to enhance resilience: leadership, technology, and the firm's experience in handling emerging events. Together, these factors help enterprises to prepare for Business Continuity Planning (BCP), improve supply chain management, and increase the firm's ability to recover from disruption situations. This paper contributes to the literature on the supply chain resilience in the automotive industry by providing a guideline for firms to implement resilience practices, improve business operations, and increase firm's capabilities, both as human skills and technologies, to deal with a novel crisis. Resilience practices response to the COVID-19 outbreak not only helps the companies minimise business disruption in the short-term but also includes the long-term response strategies for unknown events. For this purpose, the case study research was conducted to investigate the resilience strategies during the COVID-19 pandemic and determine the critical success factors of resilience implementation in the Thai automotive industry.

KEY WORDS

resilience, COVID-19, supply chains management, risk management, automotive industry, Business Continuity Plan

10.2478/emj-2021-0024

Chawalit Jeenanunta

Thammasat University, Thailand
ORCID 0000-0002-1932-9776

Corresponding author:
e-mail: chawalit@siit.tu.ac.th

Najavadh Kaeo-tad

Thammasat University, Thailand
ORCID 0000-0002-2520-5593

Kwanchanok Chumnumporn

Thammasat University, Thailand
ORCID 0000-0003-4429-1674

Thanapatra Nitisahakul

Thammasat University, Thailand

Vararat Sanprasert

Thammasat University, Thailand

Introduction

Resilience is an adequate ongoing action that aims to process lessons learned and prepare for unknown events. This leads the organisation to quick recovery and can create a safety net for such unexpected situations as the coronavirus disease (COVID-19), which was first identified in December 2019 in Wuhan, China. This emerging situation was declared a global pandemic on March 11, 2020, by the World Health Organization (WHO). The first confirmed

Kaeo-tad, N., Jeenanunta, Ch., Chumnumporn, K., Nitisahakul, T., & Sanprasert, V. (2021). Resilient manufacturing: case studies in Thai automotive industries during the COVID-19 pandemic. *Engineering Management in Production and Services, 13*(3), 99-113. doi: 10.2478/emj-2021-0024

case of COVID-19 was detected in Thailand on January 13, 2020 (Lai et al., 2020). The Thai government announced a strategy to contain the coronavirus pandemic, including wearing masks, social distancing, quarantine, and travel restrictions to (Namwat et al., 2020). However, the coronavirus mutations make it more challenging for the government to control the outbreak, especially with some infected people exhibiting no COVID-19 symptoms. COVID-19 triggered interventions aimed at reducing contacts between people, such as business restrictions, area lockdowns, and restricted movement of citizens. Such restrictions and policies are announced and enforced for individuals and organisations depending on the rate of infections in Thailand.

As the coronavirus can spread through the air, factories are concerned with outbreaks due to closed spaces, limited available floor area, and crowding. The clusters of COVID-19 infections in factories could have large numbers of workers, resulting in a rapid spread. The Thai government is concerned with the COVID-19 transmission in factories; therefore, policies for preventing, detecting, and controlling COVID-19 infections in factories have been introduced since the beginning of the outbreak. Critical security measures for factories established by the Centre for COVID-19 Situation Administration (CCSA), the Department of Disease Control under Ministry of Public Health, and the Federation of Thai Industries (FTI) can be summarised into three response roles of business owners/leaders, organisations, and individuals (workers). Business owners/leaders are required to take active action and establish centres for COVID-19 protection, determine explicit rules and policies to minimise COVID-19 disruptions, and ensure that employees strictly follow the procedures. Organisations are requested to submit to the local disease control agency plans for COVID-19 prevention in the workplace. The COVID-19 prevention plan must include standard operating procedures for screening, detecting, and tracking infections. Organisations are required to develop protocols for workplace disinfection, labour travel restrictions, and quarantine in the case of confirmed COVID-19 infections. In addition, organisations are required to rearrange the working areas, working schedules, and production plans following the social distancing restrictions. Employees are at all times request to wear masks in the workplace, self-declare their health status, and follow the COVID-19 prevention procedures stringently (Centre for COVID-19 Situation Administration, 2020; Department of Disease Control, 2021; Federation of Thai Industries, 2020). Interventions required to counteract the COVID-19 pandemic affected business operations and changed the way employees work. Virtual or remote work and online meetings were adopted for employees to work from home (WFH) (Gallup, 2020; Tortorella et al., 2021). The new normal is a challenge for the manufacturing and service sectors to operate, the resilience of businesses and supply chain management.

The coronavirus outbreak reduced the global economic growth in 2020, which continues to decline in 2021. Based on statistics recorded by the Thailand Automotive Institute, the total vehicle production of 2020 was 1 427 275 units, which is a reduction of 29 % compared to 2019. In 2020, 792 146 vehicles were sold domestically, which is a decrease of 21 % compared to 2021. The export unit of 2020 was 735 842 vehicles, which is a decrease of 30 % from 2019 (Thailand Automotive Institute, 2021a). For the first half of 2021 (January – June), the total vehicle production was 710 356 vehicles, the domestic sale was 308 211 vehicles, and the export amounted to 390 467 units. The percentage of vehicle production, domestic sale, and export units increased by 33 %, 14 %, and 30 %, respectively, compared with the same period of 2020. However, the results are diminished when compared with the same period of 2019, showing a reduction of 20 %, 30 %, and 16 %, respectively (Thailand Automotive Institute, 2021b). In 2019, Thailand ranked first as the largest automotive producer in ASEAN, fifth in Asia, and eleventh in the world (Yongpisanphob, 2020). The decreased productivity of the Thai automotive industry producers caused by the pandemic can impact the sale of vehicles and auto parts due to the disrupted global automotive supply chain. Thus, it is essential to investigate the responses of Thai automotive suppliers to the COVID-19 disruptions to prevent the supply shortage and bring sustainability to the supply chain.

The impact of the COVID-19 pandemic is considerably different from other supply chain disruptions (i.e., earthquakes, floods, civil unrests, and terrorist attacks) in two terms: (1) magnitude — the scale and duration of the impact caused by the disruption on related enterprises; and (2) duration — the time that the impact caused by the disruption on the supply chain lasted (Guan et al., 2020; Moosavi & Hosseini, 2021). Based on Nakamura and Managi (2020), an organisation should understand the short and long-term implications and reasonable risk assessments on a new phenomenon, such as the coronavirus epidemic. However, there is little data-driven

evidence to guide the global supply chains in resilience practice against the COVID-19 disruptions (Yoo & Managi, 2020).

This paper presents case studies of Thai automotive suppliers practising resilient manufacturing management in dealing with the disruption related to the COVID-19 pandemic. The article provides a conceptual framework of resilience and key success factors of resilience. The research outcome advances supply chain management research to develop a Business Continuity Planning (BCP) and adopt resilience practice used during a pandemic or any unknown situation.

The remainder of the paper is organised as follows: Section 1 provides the literature review of the relevant COVID-19 effects on business operations, new everyday procedures, the resilience definition and practices, and supply chain management. Section 2 depicts the research methodology and illustrates the structure of a semi-structured interview. Section 3 gives interview results for the three case studies. Section 4 presents thematic analysis and cross-case analysis to determine the resilience practices and key success factors, then discussing the findings. Finally, the conclusions are given.

1. Literature review

The reduction in productivity gas been influenced by national lockdowns and restrictions in different countries. Interventions triggered by the COVID-19 pandemic disrupted the entire supply chain, especially for the automotive industry. Carmakers and distributers have suffered from disturbed domestic and international logistics services. This resulted in lower orders, insufficient materials/auto parts, increased lead time, and customer dissatisfaction. Therefore, firms need to provide resilient production plans, strengthen partnerships, and implement health-related measures to avoid outbreaks in the workplace. This research is a case study analysis that aims to determine the disruption in the supply chain of the automotive industry due to the COVID-19 pandemic.

The COVID-19 pandemic affects the production of raw materials and spare parts, failing to meet the demand because of distribution difficulties. The financing risk for small to medium-sized companies and the demand fluctuation increased (Cai & Luo, 2020). Once faced with the pandemic, every country came up with plans to control the infection. Some research shows that the impact of the COVID-19 pandemic is decreased gradually, aiming to avoid more lockdowns. Earlier, stricter and shorter lockdowns should have been implemented to reduce the damage to global supply chains (Guan et al., 2020).

The pandemic disrupts healthcare and economics worldwide. Healthcare organisations face complications just as in other sectors. Supply chain leaders face challenges due to the loss of control over the situation. Nevertheless, leaders must continuously strategise, preparing for long-term change in the future (Francis, 2020). Required internal preparations for organisations include measures to ensure employee safety and sufficient product in stock to satisfy customer needs. Based on some estimations, it will take three years for the situation to recover. Under such uncertainties, leaders must be flexible and improvise, which requires continuous preparation (Lombardi et al., 2021). Yau et al. (2021) listed eight points for the management of the COVID-19 outbreak, which include fast identification of cases, enforcement of public health measures, external support (i.e., government), extra training and education for employees, personal protective equipment, organisational culture, executive level, cooperation, and hiring specialists to handle the pandemic.

Enterprises are challenged by the need to adapt rapidly to interventions triggered by the COVID-19 outbreak and minimise supply chain disruptions. This ongoing process can be considered a resilience cycle. The holistic approach to the resilience concept relies on technology and society. Scharte et al. (2014) developed a working definition of resilience as "the ability to repel, prepare for, take into account, absorb, recover from and adapt ever more successfully to actual or potential adverse events. Those events are either catastrophes or processes of change with the catastrophic outcome which can have human, technical or natural causes" (Scharte et al., 2014, p. 17). The National Academies Committee on Increasing National Resilience to Hazards and Disasters defined resilience as "the ability to prepare and plan for, absorb, recover from or more successfully adapt to actual or potential adverse events" (The National Academies 2012, p. 14). Resilience can be divided into five stages, i.e., prepare, prevent, protect, respond, and recover. The stages aim to prepare the enterprises for actual or potential adverse events. Practically implemented resilience can help enterprises advance, prepare and plan for emerging situations, cope with and recover from disasters or change processes. In

preparation, enterprises also continuously improve their ability to adapt to adverse events.

The way the whole organisation works also changed a lot during the pandemic. Employees need to follow strict regulations to prevent infection; work patterns and routines had to be revised. Firms had to adopt Industry 4.0 technologies and synchronise them with earlier solutions. This will increase production efficiency and help to alleviate the COVID-19 effect (Narayanamurthy & Tortorella, 2021). Production lines were automated. An important role in the automotive system is played by Big Data Analytics, tracking real-time information on supply chain activities to overcome the obstacles that need a high level of cooperation among stakeholders (Belhadi et al., 2021). Firms need to consider solutions they might be hesitant to use to limit the virus. Artificial intelligence (AI) and robots have been implemented by early adopters in the industry, and the idea should be considered for overcoming the crisis. Telecommuting and flexible work were applied worldwide to continue business activities without an increased risk of infection.

With the pandemic drawing towards the end, the old normal might return since the crisis may have permanently changed the way people do business. Some technologies already existed before the pandemic, but it became the factor that led to forced adoption aiming to survive (Heidenreich & Talke, 2020; Giones et al., 2020). Barriers to using technologies were broken by many users. Even though physical meetings will be brought back after the virus is eliminated, the technology will still offer an option that reduces travel costs and is less time-consuming (Brem et al., 2021). However, some challenges need to be considered while using technologies, including security, privacy, biases, ethics, and the digital divide (He et al., 2021).

The COVID-19 pandemic was unexpected and very unusual. Such situations are rare and dissimilar to other crises, which make them difficult to resolve, requiring an exclusive new strategy and plan for advance response to the health disaster and the allocation of resources, financial as well as human, with the latter requiring training and education to avoid a surge in infection cases (Peleg et al., 2021). Evidence suggests that Business Continuity Planning (BCP) had a significant influence on the supply chain (Ishida, 2020). Business Continuity Plans have been used by medium and large companies for a long time, especially those associated with foreign companies. However, since the expansion of COVID-19, Business Continuity Plans have proved crucial for every company, including small, as they also faced difficulties related to the pandemic (Margherita & Heikkilä, 2021).

Supply chain risk management and production chain performance have significant links worldwide and relationships between stakeholders and partners. Minimising risks enables firms to generate long-term benefits to all stakeholders and build a competitive position, particularly in such a confounded and moderately developing industry as the automotive industry. Globally, some most significant segments of the industry, including traveller and business vehicles, were estimated to decrease to 59.5 million units in 2020 from an optimal number of 79.6 million units in 2017. To understand the related threats and issues faced by the industry, the analysis must focus on Supply Chain Relationship Management, which should be organised to oversee everyday practice and extraordinary dangers, such as economic crises, worldwide pandemics, or other unexpected situations. Risks should be addressed carefully and responsively, checking client's requirements, changes in the chain, suppliers and competitors, technology improvements and systems to proactively recognise risks and empower the speediness of response to events, engaging in activities that allow avoiding or reducing possible effects. The essential Supply Chain Relationship Management measure comprises defining, assessing, mitigating, and monitoring hazards in the supply chain (Yoga Irsyadillah & Dadang, 2020). The risk management process requires understanding how the key enablers influence the process and how to utilise them effectively; the key enablers include flexibility, organisational learning, information systems, and performance metrics (Manuj & Mentzer, 2008).

Finally, even though companies are currently countering the effects of the COVID-19 pandemic, they still think beyond and make additional preparations for the post-crisis period to recover from the losses gained since the pandemic hit the industry (Cai & Luo, 2020).

2. Research methods

The qualitative research was done using a semi-structured interview from December 2020 until May 2021. CEOs and top managers from three automotive firms of Tier 1 shared information and experience

and discussed the effects of the COVID-19 pandemic and solutions.

Questions are formulated as a guideline, and additional questions were asked to clarify specific topics with more explanations. The questions were mainly open-ended, aiming to collect detailed information and analyse viewpoints on a particular part of the questions. The flexibility of the conversation resulted in a variety of answers. Examples of questions allowed interviewees to prepare detailed answers and ensure their reliability.

Personal interviews allowed learning in greater detail how companies went through business difficulties during the pandemic period. Due to government-imposed restrictions, some of the interviews were managed via an online meeting program, e.g., Google Meet, Microsoft Teams or Zoom. Below, an example of interview questions is shown.

- Has your organisation established policies for the prevention and management of COVID-19 cases? When was the first policy published, and did something change?
- Have there been any changes in the production after the COVID-19 outbreak, especially in the part of the rubber system?
- Have there been any changes in the communication of the firm, and if yes, what did you change? Which part of the organisation is currently using the "new normal" approach?
- In the case of the necessity to travel to an area hit by an epidemic, what strategies will you apply?
- Were any changes implemented during the first and second waves of the COVID-19 pandemic? In the case of changes introduced during the second wave, please briefly elaborate on the differences between the measures taken during the first and second waves.
- How is the organisation dealing with procurement and manages products in stock?

The analysis used the thematic method to identify the key factors. A cross-case analysis was associated with the broad topic of similarities and differences among all the cases. First, detailed information was collected for each case. Topics were determined to cluster findings into categories. When the association between the cases was found, the explanation and supporting evidence were formed to probe the relationship between the cases. Once the data was collected and organised into categories, the general direction was found in procedures used by the companies to handle the situation. The themes were divided into several topics of interest to conclude and combine key success factors for dealing with the COVID-19 pandemic. The information can be used as a guideline to manage a pandemic disruption that might occur in the future.

3. Research results

3.1. Company A

Company A was first registered as a limited company in May 1980. It was founded by a Thai and Japanese joint venture. In May 1991, it was listed on the Stock Exchange of Thailand. The vision of the company reads, "by daring to outshine light, we will pave our path to a bright future". The products include automotive lightning products (headlamp, fog lamps, rear combination lamp, solar radiation sensors, and auto-levelling unit), motorcycle lighting products (head combination lamp, rear combination lamp), auto bulb products and dies & moulds.

The deputy director and managers from related departments were interviewed in the middle of December 2020. The first COVID-19 prevention measure was introduced in February 2020 and consisted of checking every person before entering the factory. Also, alcohol gel was provided for people to use. Employees from high-risk areas with a high rate of infection had to quarantine. Space for employees to work and the dining area were limited, so different break times for employees were introduced to reduce crowding. Visitors and had to wear three layers of medical masks (fabric masks were not allowed).

The highest sales of the company were in 2019, but since the start of the COVID-19 pandemic, sales dropped to around 40 %. All measures had to be taken inside the organisation. In cases of no available work, employees were asked to stay at home. Online conferences were introduced instead of face-to-face meetings with employees working abroad. The company stated having had no problems with outsourcing or milk run. KPI was still around the same, and the company wanted to stock more, but the supplier could not send the product due to a container shortage. Also, shipping was taking longer than before.

The company did more training for employees who were less involved in production. The Human Resources Department changed some of the training procedures and methods. In addition, all of the delivered products were spayed to ensure their safety.

3.2. Company B

Company B has been in the market for 60 years, supplying parts and components for high-end international automotive brands. About 2000 employees work in the factory producing four categories of products, including parts and spare parts, OEM, Ground Support Equipment (GSE), and Logistics Solutions, participating at every level of the supply chain. The company has plants overseas and cooperates with foreign companies. It has been awarded many International Standardisation and Organisation certificates and gained much trust from other automotive brand partners. Fast improvements of the company result from being a supplier for foreign companies implementing technology transfer and auditing practise of 30 years. In its long history, the company has encountered many unexpected problems that can affect a business, e.g., the Thailand Tom Yum Kung crisis or flood in 2011. Consequently, it has a robust plan to manage such situations. Recently, the company started a cooperation with government organisations and educational institutions to develop electric vehicle technology.

The general manager of the department tasked with human capital development and organisation was interviewed at the end of March 2021. The company announced the COVID-19 prevention measures after the board committee meeting, which appointed the director to deal with the COVID-19 situation. Rules were established, including shift work for employees in manufacturing. Some departments applied to work from home. The organisation equipped a kitchen for cooking food and other necessary tools for the period of the country's lockdown. Visits were allowed only for suppliers and customers who could not conduct matters online. Strict COVID-19 prevention rules were applied in such cases. Employees were not allowed to visit the "red zone" during the holiday period, and violators risked disciplinary measures. Employees who needed to visit the "red zone" had to self-isolate and undertake a swab test for a medical statement before coming back to work. The company also developed a mobile application for employees to train them in using smartphones as primary internal communication devices. The research and development department conducted supply and procurement tasks using online channels. Technology support was provided by the government agency, science organisation, and university.

Only some departments could work from home, but the production process still needed technicians to control the machines. Most companies have no technology to remotely control the machines yet. The company can provide the device, e.g., a computer, but other problems, such as Internet access, require more investments. Most factories followed routine procedures.

For the manufacturing part, the supply chain was disrupted entirely. Some imported parts faced difficulties with orders. Due to the COVID-19 outbreak, the lead time increased by 14–15 days for China and increased the lot sizes for import products. The domestically sourced parts and products did not encounter many changes. In the middle of 2020, no export overseas was possible as almost all factories temporarily closed for several months. However, for some domestic suppliers and customers, sales were still possible. The situation in the industry is complicated. In the worst-case scenario, the company has to leave the industry. The first case was discovered in Thailand almost five months before the company recovered in the mid of 2020. The situation seemed to be getting better in 2021.

Once the situation improved, the company still faced problems because cargo ships and containers were difficult to access due to the rising demand. The prices increased, and advanced bookings were required. Sometimes, shipments were delayed, and the production and delivery had to be postponed. The company needed to work harder than usual.

Communications with suppliers and customers mostly moved online. Only necessary appointments were allowed in the factory. Regular visits, such as for education, were stopped. Meetings were conducted using online meeting applications. Delivered products were screened before entering the premises. To ensure quality control (QC), customers usually visit plants physically. During the pandemic, the visit had to be reduced from four times to two times/year. To ensure the safety and quality of products, some customer visits were still allowed, or products were sent to customers for QC and discussions held online.

For more than a year, no meetings in person between suppliers were arranged. With some countries restricting travel and requiring a fourteen-day quarantine, suppliers and customers agreed to online contacts to ensure safety. Therefore, no problems occurred in the relationships.

The company had a Business Continuity Plan (BCP) in place since before the pandemic spread to Thailand. The BCP was audited annually to test the company's readiness. The auditing experience of the company amounts to 30 years. Many successful plans

were implemented by the company in the past, such as moving the plant to the gateway to be close to their customers and reduce risks. Currently, the company has an evacuation plan for a COVID-19 outbreak in the factory.

3.3. Company C

Company C started as an automotive replacement parts manufacturer and continued expanding to the production of body parts, and eventually became a vertically integrated company with world-class manufacturing standards. Their customers are in Tier 1/2/3 Japanese automotive brands (both foreign and domestics). The company has about 800 employees. The products include plastic injection parts, lamp and mirror parts, metal standing parts, coolant parts, suspension parts, engine and brake parts, and cables and hoses. Company provided services include product design, prototype, mould design, and making and C/F, plastic injection moulding, plastic chrome plating, and plastic painting finishing and assembly.

The sustainability manager was interviewed at the beginning of May 2021. The company cooperates with Toyota as the first and second-tier supplier. It must report to Toyota monthly, with weekly supervisor visits and daily headmen checks. After the first wave of the pandemic, once the situation improved, the company exported to more than 120 countries. There is less competition for OEM and REM markets, and the company is the only company in Middle East Asia.

Discussing the manufacturing part, the respondent said that the COVID-19pandemic might be a catalyst for further development. Suppliers from China had to be replaced with partners from other countries. Fortunately, this became an opportunity to grow into the leading domestic supplier. Company C tried to source domestic raw materials as much as possible to continue with previous orders and fulfil new orders. It faced a reduction in export of 11 % but grew by 5 % domestically. The company had to deal with skyrocketing costs of shipping and containers in the fourth quarter, which increased from 30 to 500 per cent. The company had to negotiate with customers the increase in product prices due to more expensive raw materials. The company expanded their customers from B2B to B2C by launching a new 3D printing service. The majority of B2C customers ordered luxury brand parts (i.e., Porsche decoration parts).

Company C used an application for tracking employees restricted from entering "red zones". If someone accidentally went to such an area, the company required to follow a protocol, i.e., for the employee to be swabbed, quarantined, isolated, and interviewed. The pandemic in Thailand can be separated empirically into three phases. During the first phase, Company C lost many orders from global and domestic customers because more than 700 companies and partnerships closed down. The revenue remained high, but the gross profit decreased. During the second phase, Company C had issues with foreign workers because some of them left home. The hire of new foreign workers was avoided as almost all of them lived in Samut Sakhon, which was a "red zone". Company C decided to operate overtime instead; thus, it had no lay-offs or recruitments in 2020. During the third phase, the cost of raw materials escalated from 10 % to 500 %. The domestic demand was low even though the overseas demand was rising. For inventory management, Company C had a plan for at least one year. If some raw material was cheap, the company would buy large stock. No significant changes to the situation were observed during the overview.

4. Results of Thematic Analysis and Cross Case Analysis and Discussion

This section discusses and compares the three cases to identify similarities and differences based on the key processes of the resilience cycle. Five key action stages (Scharte et al., 2014) are as follow:

- Prepare — taking specific actions in anticipation of potential situations, which involve making thorough preparations for disasters, especially early warning systems.
- Prevent — eliminating some adverse events by reducing the underlying risk factors.
- Protect — ensuring that physical and virtual protection systems operate flawlessly to minimise the negative impacts.
- Respond — providing the system for rapid, well-organised, and effective disaster relief.
- Recover — bouncing back and learning relevant lessons to better prepare for future hazards or emerging events.

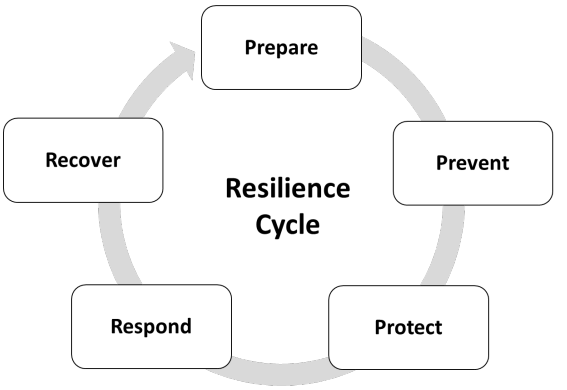

Fig. 1. Resilience Cycle

4.1. Impact of the COVID-19 pandemic on automotive companies in Thailand

The production process was significantly affected, and the biggest concern was supply chain problems during the pandemic. Some difficulties were faced importing parts from abroad during the first phase lockdown. A more extended lead time was required for import, amounting to an increase of 14–15 days from China. Also, lot sizes increased for import products as containers were not available. However, the supply of domestic parts and products did not change much. For several months during the middle of 2020, no export was possible in some companies, resulting in a serious situation in the industry. Some had to close temporarily, and in the worst-case scenario, would have to leave the industry. Even though in 2021 the situation seems to be getting better, some pandemic-related issues persist.

As automotive products and parts are heavy, exports and imports are handled through shipment. Due to the rising demand, cargo ships and containers are scares even, so difficulties remain even once countries open the territory and start shipping products again. Besides, prices are growing, and advanced bookings are required. Some shipments are delayed, requiring the postponement of production and delivery. Companies must work harder than usual. As the second wave hit the province of Samut Sakhon, the automotive industry felt the impact straightaway. However, the "red zone" covers only three districts.

Many factories located near the shrimp market have to find a solution to prevent infection among employees. Employees living nearby have to be tested for the COVID-19 infection before returning to work; otherwise, those living in risky areas have to move and stay in accommodations provided by the company.

Tab. 1. Characteristics of case studies

Characteristics of the company	Company A	Company B	Company C
Established (year)	1980	1959	1991
A spin-off from a multinational firm	Yes	No	No
Current location	Pathum Thani	Samut Sakhon	Pathum Thani
Capital structure	Joint Venture	Joint Venture	Joint Venture
Number of employees	2900+	almost 2000	800+

Product	Motorcycle bulb Rear bulb Auto bulb Dies and moulds	Trucks 4x4 Eco Truck/ Multi-Purpose Truck (MPT) Pickup Truck Solutions, Steel Canopy, and Accessories Hydraulics Axle Spared Parts Die Jig and Checking Fixture Press Steel Parts Conveyor Belt Loaders Standard Conveyor Belt Loaders with Option Container Pallet Loader Pallet Dolly Baggage Cart	Plastic injection parts Lamp and mirror parts Metal standing parts Coolant parts Suspension parts Engine and brake parts Cable and hose
Level in supply chain	Tier 1/2/3	Tier 1/2/3	Tier 1/2/3
Customer	Both domestic and oversea	Both domestic and oversea	Both domestic and oversea
Supplier	Both domestic and oversea	Both domestic and oversea	Both domestic and oversea
Factory location	Pathum Thani and China	Samut Sakhon and China	Pathum Thani and India
Experience in handling a crisis in the past	Thailand flood in 2011	The factory operated for more than 60 years and faced many crises, such as the Thailand Flood in 2011 or the Thailand Tom Yum Kung Crisis.	Thailand Floods in 2011 but did not mention in detail.
Business Continuity Plan	Did not mention.	They have been working on auditing for 30 years. Move the plant to the gateway to be close to their customers to reduce risk. Practice this evacuation plan.	BCP is available by technology, enlarging the target and risk management in several fields.

Tab. 2. Thematic analysis and cross-case studies

Resilience	Theme	Case analysis factor	Company A	Company B	Company C
1. Preparation	Human Resource Management	Communication channel	Telecommunication Video conference	COVID-19 forced them to change to digitisation. Use their application to communicate	Telecommunication Video conference
		Employee tracking system	No, but employees not allowed to go to the high-risk areas	No. Only monitoring by asking employees directly	Yes
		The most concerning issue	Concern about employees' mobility because they are not working from home if there is no lockdown	Concern about employee mobility because of almost 2000 employees and the COVID-19 infection outside the factory as it is impossible to control where employees go	Work overload due to the lack of migrant labour and concerns about the outbreak from employee dormitory/ community
		Company support	Supporting COVID-19 testing upon return from a trip abroad and prepare a space for them to quarantine	Support employees in skills improvement, including learning to use technologies to be able to work from home during the pandemic	Support the COVID-19 testing, no downsizing, increased OT support, employee skills training and application at work
2. Prevention	Strategic Management	Role of leadership	The factory appointed a responsible manager, and it was a successful decision	The manager acted fast and provided clear regulations to be followed consistently. The manager was respected and trusted	Strong at information technology, applying the technology to eliminate waste time processes (lean operation), and using technology to survive, i.e., 3D printing for B2C
		Online for internal use	Yes	Yes	No
3. Response	Engineering	Introduction of new technology	Did not mention	Order suppliers online and develop electric vehicle technology	Internal application for tracking employees. 3D Printing technology
		Product design	Some employees design products for customers	Has an R&D department, cooperates with government organisations and educational institutions. Use drawings to discuss via online meetings	R&D uses CAD files as the primary channel between the company, customer and supplier
		Quality Control (QC process)	Online but customer employees to stay in Thailand to help to do QC	Keyman still visits the customers but at a reduced frequency from 4 to 2 times/year	Customer's employees work in the firm to conduct QC methods and verify by a certificate from third parties in Europe
		Technology transfer from supplier or customer	Yes, from a customer	Yes, from a customer	Yes, from a customer
	Transportation Issues	Export products during the pandemic	Less export as not enough containers	No export	Export decreasing by 11 % but domestic growth by 7 %
		Import parts during the pandemic	Take a longer time to arrive since there is no container	The long lead time for import increased by 14–15 days from China and might cause delays. The increased lot size for import products	Lack of importing from China, using local suppliers, the price is low because the domestic demand is low
		Difficulty in shipment	Increased prices and containers are difficult to get	Increased prices and containers are difficult to get	Increased prices and containers are difficult to get

4. Recover	Sale	COVID-19 effect on the sale	The sale is about 40 % lower than usual	Sales recovered but not fully to 100 %. Less overseas customers	Sales increased because many suppliers and customers purchase from this firm instead of China. Suppliers in China cannot export any products
5. Protect	Human Resource Management	Vaccination	No, which is on the interview date (December 15, 2020)	Yes. Some of the employees who live in Samut Sakhon province have an interview date (March 31, 2021)	No, which is on the interview date (April 19, 2021)
		New normal on working condition	The manufacturing section still works on-site but is divided into 2 groups and works in shifts, the other employees work at different times. Very strict for temperature checking and zoning. Allow work from home for the back-office department, such as accounting, marketing, etc.	The manufacturing section still works on-site. Employees who live in risky areas quarantine at home and test for COVID-19 before returning to work. Allows work from home for the back-office department, such as accounting, marketing, etc.	The manufacturing section still works on-site but is divided into 2 groups and works in shifts, the other employees work at different times. Allows work from home for the back-office department, such as accounting, marketing, etc. Very strict with temperature checking and zoning

4.2. New normal within automotive businesses

The COVID-19 outbreak is a new situation, which has not yet been brought under control. This unpredictable event requires massive changes in usual work routines. Business leaders have to act very fast to handle the effects. Managers have to be tasked with communicating to everyone consistently to understand the message in the same way. Clear rules and regulations have to be enforced in the company and correspond to the rules from the government, including social distancing, wearing of a face covering, and the disinfection of the workplace. All imported materials or parts have to be disinfected before shipping and once received, to get rid of possible infection. For safety, work at crowded floor areas had to be reorganised into shifts on-site, and more work had to be allowed from home. Regular handwashing was mandatory. For employees, travel to risky zones was prohibited with imposed disciplinary measures in the case of failure to comply. To ensure business operation, some employees had to be provided with accommodation and food due to the inability to return home to an area deemed risky. Although Thailand has fewer cases of infection compared to other countries, the strict policy continues. Employees will be monitored and screened before entering the factory for personal and public health safety. The Thai government policies in the short-term strategies anticipate rescheduling of working hours and work-from-home schemes.

All case studies had clear restrictions for social distancing, quarantine, and travel restrictions. Thus, they can prevent and control the COVID-19 infection internally and become resilient manufacturers. The findings support the previous study by Rajak et al. (2021), stating that social distancing is important for sustainable initiatives in the supply chain during the COVID-19 pandemic. For supply chain resilience, the firms increased the inventory turnover ratio and recruited local firms as suppliers to prevent the supply shortage. These strategies of the case studies in Thailand can be confirmed by Belhadi et al. (2021), stating that localisation of supply sources is the best strategy to mitigate risks related to supply chain resilience during the coronavirus epidemic in the automotive industry. Moosavi and Hosseini (2021) found that extra inventory resulted in a higher resilience than a backup supplier. However, the companies require to absorb the greater cost.

4.3. Technology involvement during the pandemic

When the COVID-19 pandemic affected the world and almost made it stop, the data exchange and dissemination were recognised as crucial processes in the healthcare sector and other fields, such as the economy, community, and industry. Many prevention strategies have been prompted by the emergence of the COVID-19 pandemic in the industry sector, e.g., transportation restrictions and lockdown. Technology is the key factor for new normal practices, especially Industry 4.0 technologies. Firstly, the communication with suppliers and customers changed from company visits to telecommunications using online meetings or assigning employees who stay in partner companies to conduct quality control or design new products. Secondly, the companies took the opportunity to enlarge their market by launching new services and purchasing new machines when the prices dropped. Thirdly, the traditional sale process (face-to-face) is changed to completely online. Some companies built their platform to accommodate online orders, which helped them to save costs and create opportunities in finding new customers. Fourthly, some companies developed a healthcare application to track employee health status and travel. New technologies implemented during the pandemic have changed business operations and production processes for the period of the current disruption and for post-COVID-19. Thus, the use of emerging technologies during disruptions can be considered a long-term response strategy. This outcome supports findings by Belhadi et al. (2021) that advanced Industry 4.0 technologies aim to reduce the COVID-19 disruptions in the automotive industry. In addition, the real-time information on various supply chain activities shared among stakeholders plays an essential role in overcoming the challenges of the COVID-19 outbreak (Belhadi et al., 2021). The resilience practices using digital technologies confirmed the initial research by Ivanov et al. (2019) and Ralston and Blackhurst (2020), stating the aim of digital technologies to enhance supply chain resilience. Digital technologies, such as the Internet of Things (IoT), Big Data, and Digital Twin, improve high connectivity, accuracy, and transparency between supply chain stakeholders (Hofmann et al., 2019; Kamble & Gunasekaran, 2020).

4.4. Technology transfer from supply chain partners and the experiences from past crisis events

During the pandemic, the automotive industry was affected by a lack of remote working options. Manufacturing was nearly suspended at the beginning of the second quarter, and demand dropped, leading businesses to significant financial losses. Automobile firms must work hard to recover from the inactive manufacturing time as production gradually resumes. All the three firms of the case studies were Tier 1; they had transferred the technology and innovation from their partners. One of the partners was Toyota, which had transferred the production system to its customers. Each firm tried to apply and develop a production system. Since the companies had operated for more than twenty years, they faced crises, disasters, and other global events, e.g., Tom Yum Kung Financial Crisis in 1997 and Thailand Floods in 2011. However, the COVID-19 pandemic differs from natural disasters or human-made interruptions (Guan et al., 2020). The duration and magnitude of the coronavirus outbreak (the scope of the disruption's impact on related enterprises) are catastrophic compared to other experienced disruptions (Moosavi & Hosseini, 2021). The knowledge and BCP transferred from partners were the fundamental measures in overcoming the risk related to the pandemic. This finding is supported by Belhadi et al. (2021), stating that collaboration among supply chain stakeholders aims to accelerate digital technology implementation and build a resilient manufacturing operation.

4.5. Major concerns for the pandemic

Human resources are the most important in the industry, and not the machines or capital. All three firms were concerned about the behaviour of their employee during the COVID-19 pandemic because almost all employees had no car and stayed in dormitories. Employees can be infected easily in the living environment, such as a market, dormitory, or other communal spaces. In the case of a large number of infected employees, the entire area is treated as a COVID-19 cluster and requires a quarantine of 14 days. In addition, the firms required their staff to avoid risk, and the recruiting process was stricter for screening new employees. Migrant employees from

"red zones" were not allowed to apply or arrive for an on-site interview. Some companies had to stop the recruiting process for the COVID-19 pandemic or conduct it online. These processes of the "new normal" are consistent with short-term strategies of the Thai government, as mentioned in the introduction (Centre for COVID-19 Situation Administration, 2020; Department of Disease Control, 2021; Federation of Thai Industries, 2020).

Conclusions

The COVID-19 pandemic disrupted the automotive industry and supply chain management. Keys to surviving the COVID-19 disruption have three components, i.e., leadership, experience, and technology. These three keys result in preparation for similar cases, e.g., putting Business Continuity Plans and/or risk management plans in place. Leadership is the most important factor in foresing the future and opportunities, helping the company to turn threats into success. During the COVID-19 pandemic, companies encounter the "new normal" that forces them to rearrange business operations as well as improve production processes. A good example from the case studies was investments in new technologies to improve production processes and enhance productivity. Additionally, companies use the advantage to train employees by upskilling, reskilling and providing new skills. The employees understand the need for technologies and have less resistance towards the adoption of new technologies.

Another example is that some firms invested in creating the COVID-19 control centre to provide consistent information and apply strategies for containing the spread of the COVID-19 infection. Applications can be used to track and update the health status of infected employees.

Technology helps to create automation systems and share different data inside and outside the company. Upgraded telecommunication is one of the strategies that almost every organisation used during this crisis. Even once the COVID-19 pandemic is over, computing technologies will continue to play a major role, especially in reassessing policy responses. Therefore, it is important to support stakeholders in the implementation and improvement of strategies to prepare for similar potential significant disruptive events in the future.

Finally, experience in handling the emerging situation is of utmost importance. After the second and third wave of the infection, almost all large companies had their Business Continuity Plan designed to prevent and prepare for similar cases that might occur in the future. Thus, the "new normal" arising from the COVID-19 pandemic is perceived as experiences comparable to previous cases, e.g., Avian Influenza (Bird Flu), the Swine Flu Pandemic in 2009, Thailand Floods in 2011. These emerging situations force companies to prepare Business Continuity Plans (BCP), which provide an advantage in terms of resilience for the production processes and supply chain management.

Acknowledgements

The authors would like to express their gratitude to Ms Rusameekhair Wongchadakul, Deputy Director (Executive), Ms Jeeraphan Suktavee, Safety and Environment Manager, Ms Marisa Chukittipong, Human Resource Manager, and Ms Piyaporn Thongprasert Client Service of Environment & Energy Section from Thai Stanley PLC. Mr Anan Piammanustham, General Manager Human Capital Development and Organization Department, Mr Wanchai Suvarnmanee, Affair and Employee Relationship Manager from Sammitr Motors Manufacturing PLC., Dr Saruda Siripatpricha, Sustainability Manager and Ms Sutima Sukboon from Fortune Industry Parts PLC.

This research is fully supported by the Center of Excellence in Logistics and Supply Chain Systems Engineering and Technology (CoE LogEn), Sirindhorn International Institute of Technology, Thammasat University.

The publication of the article for the 11th International Conference on Engineering, Project, and Production Management — EPPM2021 was financed within the framework of contract no. DNK/SN/465770/2020 by the Ministry of Science and Higher Education within the "Excellent Science" programme.

Literature

Belhadi, A., Kamble, S., Jabbour, C. J. C., Gunasekaran, A., Ndubisi, N. O., & Venkatesh, M. (2021). Manufacturing and service supply chain resilience to the COVID-19 outbreak: Lessons learned from the

automobile and airline industries. *Technological Forecasting and Social Change*, *163*, 120447. doi: 10.1016/j.techfore.2020.120447

Brem, A., Viardot, E., & Nylund, P. A. (2021). Implications of the coronavirus (COVID-19) outbreak for innovation: Which technologies will improve our lives? *Technological Forecasting and Social Change*, *163*, 120451. doi: 10.1016/j.techfore.2020.120451

Cai, M., & Luo, J. (2020). Influence of COVID-19 on Manufacturing Industry and Corresponding Countermeasures from Supply Chain Perspective. *Journal of Shanghai Jiaotong University (Science)*, *25*(4), 409-416. doi: 10.1007/s12204-020-2206-z

Department of Disease Control. (2021). The COVID-19 precautionary, prevention, and control measures for entrepreneurs. Retrieved from https://ddc.moph.go.th/viralpneumonia/file/int_operator/int_operator23_050164.pdf

Francis, J.R. (2020). COVID-19: Implications for Supply Chain Management. *Frontiers of Health Services Management*, *37*(1), 33-38. doi: 10.1097/hap.0000000000000092

Gallup. (2020). How Leaders Are Responding to COVID-19 Workplace Disruption. Retrieved from https://www.gallup.com/workplace/307622/leaders-responding-covid-workplace-disruption.aspx.

Giones, F., Brem, A., Pollack, J. M., Michaelis, T. L., Klyver, K., & Brinckmann, J. (2020). Revising entrepreneurial action in response to exogenous shocks: Considering the COVID-19 pandemic. *Journal of Business Venturing Insights*, *14*, e00186. doi: 10.1016/j.jbvi.2020.e00186

Guan, D., Wang, D., Hallegatte, S., Davis, S. J., Huo, J., Li, S., Bai, Y., Lei, T., Xue, Q., Coffman, D., Cheng, D., Chen, P., Liang, X., Xu, B., Lu, X., Wang, S., Hubacek, K., & Gong, P. (2020). Global supply-chain effects of COVID-19 control measures. *Nature Human Behaviour*, *4*(6), 577-587. doi: 10.1038/s41562-020-0896-8

He, W., Zhang, Z. J., & Li, W. (2021). Information technology solutions, challenges, and suggestions for tackling the COVID-19 pandemic. International Journal of Information Management, *57*, 102287. doi: 10.1016/j.ijinfomgt.2020.102287

Heidenreich, S., & Talke, K. (2020). Consequences of mandated usage of innovations in organizations: developing an innovation decision model of symbolic and forced adoption. *AMS Review*, *10*, 279-298. doi: 10.1007/s13162-020-00164-x

Hofmann, E., Sternberg, H., Chen, H., Pflaum, A., & Prockl, G. (2019). Supply chain management and Industry 4.0: conducting research in the digital age. *International Journal of Physical Distribution & Logistics Management*, *49*(10), 945-955. doi: 10.1108/IJPDLM-11-2019-399

Ishida, S. (2020). Perspectives on Supply Chain Management in a Pandemic and the Post-COVID-19 Era. *IEEE Engineering Management Review*, *48*(3), 146-152. doi: 10.1109/emr.2020.3016350

Ivanov, D., Dolgui, A., & Sokolov, B. (2019). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *International Journal of Production Research*, *57*(3), 829-846. doi: 10.1080/00207543.2018.1488086

Kamble, S.S., & Gunasekaran, A. (2020). Big data-driven supply chain performance measurement system: a review and framework for implementation. *International Journal of Production Research*, *58*(1), 65-86. doi: 10.1080/00207543.2019.1630770

Lai, C. C., Shih, T. P., Ko, W. C., Tang, H. J., & Hsueh, P. R. (2020). Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and coronavirus disease-2019 (COVID-19): The epidemic and the challenges. *International Journal of Antimicrobial Agents*, *55*(3), 105924. doi: 10.1016/j.ijantimicag.2020.105924

Lombardi, S., Pina E Cunha, M., & Giustiniano, L. (2021). Improvising resilience: The unfolding of resilient leadership in COVID-19 times. *International Journal of Hospitality Management*, *95*, 102904. doi: 10.1016/j.ijhm.2021.102904

Manuj, I., & Mentzer, J. T. (2008). Global supply chain risk management. *Journal of Business Logistics*, *29*(1), 133-155. doi: 10.1002/j.2158-1592.2008.tb00072.x

Margherita, A., & Heikkilä, M. (2021). Business Continuity in the COVID-19 Emergency: A Framework of Actions Undertaken by World-Leading Companies. *Business Horizons*.

Moosavi, J., & Hosseini, S. (2021). Simulation-based assessment of supply chain resilience with consideration of recovery strategies in the COVID-19 pandemic context. *Computers & Industrial Engineering*, *160*, 107593. doi: 10.1016/j.cie.2021.107593

Nakamura, H., & Managi, S. (2020). Airport risk of importation and exportation of the COVID-19 pandemic. *Transport Policy*, *96*, 40-47.

Namwat, C., Suphanchaimat, R., Nittayasoot, N., & Iamsirithaworn, S. (2020). Thailand's response against coronavirus disease 2019: challenges and lessons learned. *OSIR*, *13*(1), 33-37.

Narayanamurthy, G., & Tortorella, G. (2021). Impact of COVID-19 outbreak on employee performance – moderating role of industry 4.0 base technologies. *International Journal of Production Economics*, *234*, 108075. doi: 10.1016/j.ijpe.2021.108075

Peleg, K., Bodas, M., Hertelendy, A. J., & Kirsch, T. D. (2021). The COVID-19 pandemic challenge to the All-Hazards Approach for disaster planning. *International Journal of Disaster Risk Reduction*, *55*, 102103. doi: 10.1016/j.ijdrr.2021.102103

Rajak, S., Mathiyazhagan, K., Agarwal, V., Sivakumar, K., Kumar, V., & Appolloni, A. (2021). Issues and analysis of critical success factors for the sustainable initiatives in the supply chain during COVID-19 pandemic outbreak in India: A case study. *Research in Transportation Economics*, 101114. doi: 10.1016/j.retrec.2021.101114

Ralston, P., & Blackhurst, J. (2020). Industry 4.0 and resilience in the supply chain: a driver of capability enhancement or capability loss? *International Journal of Production Research*, *58*(16), 5006-5019. doi: 10.1080/00207543.2020.1736724

Scharte, B., Hiller, D., Leismann, T., & Thoma, K. (2014). Introduction. In K. Thoma (Ed.), *Resilien Tech. Resilience by design: a strategy for the technology issues of the future (acatech STUDY)* (pp. 9-17). München, Germany: Herbert Utz Verlag.

Thailand Automotive Institute (2021b). Automotive Industry Statistics & Trends of June 2021. Retrieved from https://data.thaiauto.or.th/auto/articles-th/auto-summary-th/148-auto-industry-status-monthly/9831-สภาวะอุตสาหกรรมยานยนต์-รายเดือน-พฤษภาคม-2564.html

Thailand Automotive Institute. (2021a). Automotive Industry Statistics of Year 2020 & Trends of Year 202. Retrieved from https://data.thaiauto.or.th/auto/articles-th/auto-summary-th/150-auto-industry-status-yearly/9692-summary-yearly-2565.html

The Centre for COVID-19 Situation Administration. (2020). The manual guideline of relief measures for business activities to prevent the COVID-19 pandemic: Business activities group 2. Retrieved from https://ddc.moph.go.th/viralpneumonia/file/guidelines/guideline_green_covid19.pdf

The Federation of Thai Industries. (2020). The guidelines of COVID-19 prevention for industrial sector. Retrieved from http://www.fti-rayong.com/wp-content/uploads/2020/12/แนวปฏิบัติ-8-กลุ่มอุตสาหกรรมยิงยวด_FTI_JUNE.pdf

The National Academies. (2012). Disaster Resilience. A National Imperative. Washington, D.C.

Tortorella, G., Narayanamurthy, G., Godinho Filho, M., Portioli Staudacher, A., & Mac Cawley, A. F. (2021). Pandemic's effect on the relationship between lean implementation and service performance. J*ournal of Service Theory and Practice*, *31*(2), 203-224.

Yau, B., Vijh, R., Prairie, J., McKee, G., & Schwandt, M. (2021). Lived experiences of frontline workers and leaders during COVID-19 outbreaks in long-term care: A qualitative study. *American Journal of Infection Control*, *49*(8), 978-984. doi: 10.1016/j.ajic.2021.03.006

Yoga Irsyadillah, N., & Dadang, S. (2020). A Literature Review of Supply Chain Risk Management in Automotive Industry. *Journal of Modern Manufacturing Systems and Technology*, *4*(2), 12-22. doi: 10.15282/jmmst.v4i2.5020

Yongpisanphob, W. (2020). Industry Outlook 2020-2022: Automobile Industry. Krungsri Research. Retrieved from https://www.krungsri.com/en/research/industry/industry-outlook/Hi-tech-Industries/Automobiles/IO/io-automobile-20

Yoo, S., & Managi, S. (2020). Global mortality benefits of COVID-19 action. *Technological Forecasting and Social Change*, *160*, 120231. doi: 10.1016/j.techfore.2020.120231

Volume 13 • Issue 2 • 2021

sciendo

ISMSME International Society for Manufacturing, Service and Management Engineering

received: 20 February 2021
accepted: 31 July 2021

pages: 114-126

Gerontechnology — new opportunities in the service of older adults

Katarzyna Halicka Dariusz Surel

ABSTRACT
The increasingly more visible trend of population ageing necessitates creating technologies supporting the functioning of older adults. Consequently, more gerontechnologies emerge designed to help the older adults in their daily functioning, from devices monitoring the health to special trolleys improving the mobility or Virtual Reality devices for active learning. This article aimed to determine the most desired group of gerontechnologies among current and future users. It focused on individual assessments of the most desirable group of gerontechnologies based on various criteria. The investigation aimed to find the criterion rated the highest in the selected group of gerontechnologies. The gerontechnology group was assessed against seven groups of criteria distinguished by the authors, i.e., Technology Innovation, Technology Demand, Social and Ethical Criteria, Technology Usability, Technology Functionality, Technology Ease of Use and Technology Use Risk. The survey was conducted in the form of a questionnaire, using CAWI (Computer-Assisted Web Interview) and CATI (Computer-Assisted Telephone Interview) methods, with the research sample comprised of 1 152 residents of Poland. Thus far, no studies have been conducted to evaluate this group of technologies based on the above-mentioned criteria.

KEY WORDS
gerontechnology, technology, health, analysis, older adults

10.2478/emj-2021-0025

Dariusz Surel

Bialystok University of Technology, Poland
ORCID 0000-0003-1174-5545

Corresponding author:
e-mail: d.surel@doktoranci.pb.edu.pl

Katarzyna Halicka

Bialystok University of Technology, Poland
ORCID 0000-0001-6370-8995

Introduction

In recent years, the ageing society trend has become increasingly more distinct. 2019 saw 703 million persons aged 65 years or over worldwide, and the number is projected to double to 1.5 billion in 2050 (United Nations, 2019). All world regions will see an increase in the size of their older populations between 2020 and 2050, and the share of the global population aged 65 years or over is expected to increase from 9.3 % in 2020 to 16 % by 2050. As in other European

Halicka, K., & Surel, D. (2021). Gerontechnology — new opportunities in the service of older adults. *Engineering Management in Production and Services, 13*(3), 114-126. doi: 10.2478/emj-2021-0025

countries and the rest of the world, the phenomenon of an ageing society is evident in Poland. In the first half of 2020, the population of Poland was over 38 million (38 354 173), of which over 7 million were aged 65 years and older (Central Statistics Office Poland, 2020). For comparison, in 2019, the number of older people (aged 65 and over) was less than 7 million (6 947 019) (Central Statistics Office Poland). The data show a growing number of older adults in Poland, and this trend may continue in the future.

The ageing phenomenon may have several causes. Based on Cursaru, the main factors of population ageing are declining fertility rates and increasing life expectancy, which was much lower in the 19th century (Cursaru, 2018). The ageing population can be considered a negative phenomenon due to greater strains on budgets for pensions, medical care or various benefits (Jarocka & Wang, 2018). The ageing trend is also largely related to the improvement of living conditions and a wider and more developed healthcare system. Increasing numbers of older adults also want to take care of their physical and mental health, which directly translates into longer life.

The silver economy is worth mentioning in raising the issue of population ageing. The concept of the silver economy is defined as a considered part of the general economy that is relevant to the needs and demands of older adults (European Union Publications Office, 2018). Klimczuk (2016) defined the concept of the silver economy as a system based on adapting the production and distribution of products and services to older adults and, consequently, to all age groups. This ideal of an economic system originated in Japan, centred on the diverse needs of seniors (Klimczuk, 2011). Another definition of the silver economy proposed by Oxford Economics defines it as "the sum of all economic activity serving the needs of those aged 50 and over including both the products and services they purchase directly and the further economic activity this spending generates" (Oxford Economics). In the past, the silver market concept has also been used, defined as an industry modifying existing products to increase their usability to older consumers (Zimnoch, 2013). The concept of the silver economy seeks to look holistically at ageing and also the opportunities it presents, bearing on the future direction of a broad range of policies, such as those on the built environment, life-long learning, 50+ employment, and preventive healthcare (Bojanić & Erceg, 2017). The European Commission also defines the silver economy as economic opportunities arising from the public and consumer expenditure related to population ageing and the specific needs of the population over 50 (European Commission, 2015).

While focusing on population ageing and the silver economy, gerontechnology has become a significant area of science. Based on international and national programmes or scientific research activities, the need for technological development has become widespread (Halicka, 2020). Nowadays, technologies are developing incredibly fast, and the ageing society necessitates the design of technologies dedicated to older adults who often need support in different areas of life. This demand can be met with the help of gerontechnology — a combination of gerontology and technology. Gerontology may be defined as a scientific study of ageing that examines the biological, psychological, sociological factors associated with old age and ageing (Brossoie, 2018). At the beginning of the development of gerontechnology, Bouma (1992) defined this area of science as a "study of technology and ageing for the improvement of the daily functioning of the older adults". Based on Rzeczynski (2009), this field focuses on the social and environmental aspects of older people. Another definition is that gerontechnology can help older adults identify and slow down the effects of age-related modifications of the neural and musculoskeletal systems (Sale, 2018). According to Boruta (2017), the growing caring needs of an ageing society cannot be met only with the increase in the number of carers; thus, technologies should be developed to assist older people. Also, gerontechnology officially became an academic field at the First International Congress on Gerontechnology, which was held in 1991 in Eindhoven, the Netherlands (Hsu & Li Bai, 2016).

In the development of gerontechnology, research should focus on technologies improving the quality of life of older people. The related literature offers various studies on technologies supporting older adults. Halicka and Ejdys (2018) conducted a study on humanoid robots designed to provide care to older adults and the related attitude towards such technologies. Researchers from the USA studied the use and understanding of social communication technologies by older adults and their attitude towards this type of technology (Bixter et al., 2019). Older people may encounter problems with memory and memorising, so another study focused on memory notebooks and their usefulness (Dahmen et al., 2018). Over time and with the increasing ageing trends within the population, there is a need to conduct research on technologies that make life easier for older adults. Increasingly

more advanced technologies emerge and must be carefully analysed, also assessing the users' approach to such technologies. The subject of gerontechnology is relatively well known globally yet might be somewhat new for some people in Poland. As a niche topic in Poland and worldwide, gerontechnology requires more research on technologies improving the quality of life of older people. In the aim to develop the gerontechnology sector in Poland, opinions, approaches and needs related to gerontechnology should be recognised.

1. Literature review

There are many different types of gerontechnologies, ranging from modern mobile wheelchairs through systems monitoring houses and flats, ending with various health applications or robots supporting the functioning of older adults. These are just some examples of the technologies helping older people in their everyday functioning. Different technologies may need to be separated into individual categories or groups. There is no single universal, generally accepted classification of gerontechnologies; however, the related literature proposes several classifications. Based on a detailed analysis of the literature, this article proposes another classification of gerontechnologies into nine main groups, i.e., Health, Education, Interpersonal Communication, Safety, Mobility, Care, Leisure, Housing, and Digital Accessibility (Halicka & Surel, 2020).

The first group of technologies is related to the broadly understood health of older people. This group includes all technologies involved in the care for and monitoring of human health, also including telehealth and telemedicine technologies. A good example of technology that falls into the health category is the Amulet Device (Batsis et al., 2018), which looks like a smartwatch with dimensions of 4 cm2, a slider with a black and white screen, and two buttons. The device can run applications tracking and monitoring health, i.e., activity, stress, strength, steps. The collected data can be stored on a micro-SD card or transmitted over Bluetooth to a tablet or smartphone. Another great example of such technology is an electronic pillbox (eMMD) (Tellier et al., 2020). The device consists of a connector and 28 compartments covered with a membrane that detects motion. Each compartment can hold several pills. When the time comes to take medicines, eMMD sends a sound alert and switches a green light indicator on the compartment with pills to be taken. This technology can help older people by reminding them to take medicines at the right time.

Another group of gerontechnologies are related to education. With the growing popularity of third age universities, other education solutions are being created for older adults, such as applications for tablets/smartphones for learning, e.g., foreign languages. Digital learning games make learning for older people accessible and enjoyable. A good example of such a game is LEAGE. The game aims to help older people improve their competencies by practising and expanding knowledge on topics of history, geography, nutrition, health problems by motivating exercises and memory training (Nap et al., 2014). This game is available in two versions (one played by a TV remote control on a Set-Top Box, and the other using a 3D Microsoft Kinect sensor), helping older people to learn different knowledge in a very interesting and active way.

Interpersonal Communication is the third group of technologies supporting older adults facing issues related to communication with others. Thus, this group of technologies is mainly based on facilitating interpersonal communication between older adults, their families and friends. To make communication easier, simplified smartphones are offered, e.g., with larger keys and screens (Assisted Living Today). Video calls may be a great convenience for older adults making it possible to see members of their families. Various special devices are available, making communication easier and user-friendlier for older adults.

Safety is of the utmost importance to the functioning of older people; therefore, the fourth group of gerontechnologies concerns this type of solution. E.g., these technologies can inform families that something may have happened to their older adult. A technology that fits well into this group is the smartphone application SteadyTM (Hsieh, Fanning & Sosnoff, 2019), which was developed specifically for older adults, considering their unique usability preferences and needs (Bernard, Liao & Mills, 2001). The application consists of two components that compute a fall risk score (Hsieh et al., 2018), where the first component is a 13-item questionnaire of health history (age, gender, number of falls in the last year, perceived balance confidence). The second component is a progressive postural stability test, which guides the user through five balance tasks of progressive difficulty. This information, together with data from the health history questionnaire, is entered

into a weighted algorithm to produce a score and classification of a degree of the fall risk (very low, low, moderate, high and very high).

Mobility issues become more problematic with age as well. Older people may have difficulty climbing stairs; some use various aids to help with movement. The 5th group of gerontechnologies concerns the broad subject of mobility. Advancing wheelchair technologies are available to people with serious legs and back problems. The ordinary wheelchairs controlled and driven by muscle power (either by the wheelchair user or a helper) are replaced by technologies controlled using a joystick. This solution requires a wheelchair user to have a fit hand and may be inaccessible to paralysed people. Rapidly developing technologies offer other types of control, i.e., by eye or mouth movement. Another good example of mobility technologies is the SMILING Shoe, which is a complex mechatronic system requiring the interaction of mechanical components, human activity and various sensor data. The shoe is worn on a standard shoe, and the user has to react to changes of shoe inclinations to keep balance while walking and completing different, specific tasks (Simsik, 2012). This device might be very helpful in the rehabilitation of older adults.

Another very important group of gerontechnologies focuses on caring for seniors, which is an extremely important and time-consuming activity. Seniors are often unable to cope with all everyday life tasks, thus requiring assistance. As family members do not always have enough time, other solutions must be found. Robots can bring a great change in the relationship between humans and technologies, making the issue of older people's trust in future technologies especially significant (Ejdys, 2018). Nowadays, greater emphasis is placed on the development of artificial intelligence and various types of robots. Therefore, scientists and engineers focus on building and developing robots to take care of older adults. Wieczorek (2016) reviewed two types of robots used in the care for older adults: social robots communicating with the user and assistive robots. Halicka (2019) studied how robots were evaluated against various criteria and whether the age and gender of respondents influenced the evaluation of the technology. Robots caring for older adults can be a revolutionary solution. It can put older adults at the ease of knowing that help is always available and relieve younger family members of additional duties. Also, robots could take over a large part of duties currently performed by professionals (e.g., nurses), such as helping older adults to move around. A good example of such a robot is Robear. This nursing robot can help older people by lifting them from a bed to a wheelchair, provide support while standing (if required) (RoboticsBIZ). Another great example is a robot named Care-O-bot (Care-O-bot), which can also help older adults in their daily lives. It is intended to be an affordable care option with six configurable models depending on the available budget and needs (RoboticsBIZ).

It is important to provide adequate entertainment for older people who have free time. Dynamically developing technologies also focus on the leisure of older adults. This type of technology is covered by the seventh group of gerontechnologies in the classification.

Home safety is yet another important topic for older adults. This type of technology is covered by the group of gerontechnologies called "Housing" and includes various monitoring systems, hazard detection devices and technologies that automatically notify relevant emergency services or family members. Also, the group includes various types of devices and solutions that make it easier for seniors to function independently in their homes.

The last group of gerontechnologies is named "Digital Accessibility". Older people may want to use technologies but feel reluctant because of the fear they would be too advanced or difficult to learn. Older people may encounter considerable problems with the use of smartphones or computers. As these devices are essential for communication, messaging, and information, such as the weather, engineers create special devices that are easy to use for older adults, ensuring easy access to such technologies.

To be able to market and develop the abovementioned groups of technologies improving the quality of life of older people, it is necessary to assess these technologies against various criteria, e.g., innovation, usability, functionality, demand for a particular class of technology, ease of use or ethics. It is also necessary to identify the most desirable gerontechnology groups for current and future users. So far, both globally and in Poland, no such research has been conducted. The existing research only concerns the degree of acceptance of the technologies that improve the quality of life for older people. The opinions of future or potential users have not been considered either. The literature also presents research on one arbitrarily chosen gerontechnology. No studies were conducted to assess different classes of gerontechnologies.

The analysis and assessment provided in this article were made considering different criteria of the nine above-mentioned classes of gerontechnologies. The literature studies and exploratory research conducted so far allow the following research questions to be formulated: (1) Which of the nine gerontechnology groups is most desired by current and future users? (2) What are the individual assessments of future and current users of the most desirable gerontechnology depending on the type of criteria? (3) For which criterion has the selected, most desirable group of gerontechnologies been rated the highest?

2. Research methods

A survey was carried out in early 2020 to assess the nine gerontechnology groups considering various criteria and to identify the most desirable gerontechnology for users. The survey sample was representative and amounted to 1 152 Polish citizens over 40 years of age. The survey was conducted using CATI (Computer-Assisted Telephone Interview) and CAWI (Computer-Assisted Web Interview) methods.

In the sample structure, 26.3 % (303 people) were aged 40–49, 28.6 % (329 people) were aged 50–59 and 45.1 % (520 people) were over 60. Men comprised 45.7 % (527 people) of the sample and 54.3 % (625 people) were women.

The survey was conducted among the inhabitants of Poland. The smallest group of respondents came from cities with 150 000 – 250000 inhabitants (9.8 %, 113 people) and cities with up to 20 thousand inhabitants (11.1 %, 128 people). The largest groups of respondents came from cities with over 250 000 inhabitants (26.5 %, 305 people) and from cities with 50 000 – 150 000 inhabitants (19.2 %, 221 people).

The vast majority of respondents had secondary education (45.8 %), some (9.5 %) had only primary education, over 25 % of the respondents had a higher education degree. The rest of the respondents (19 %) had vocational education.

3. Research results

The respondents were asked which of the nine gerontechnology groups were the most desired by current and future users. The most important group of gerontechnologies was related to the health (G1) and safety of older adults. The third and fourth places were given to the "Care" group and the "Interpersonal Communication" group. The following ranks were given to "Mobility", "Education" and "Leisure". The least important groups were "Housing" and "Digital Accessibility".

As the most important gerontechnology group was related to health, it assessed in detail, considering various criteria. Initially, on the basis of the literature review, the following criteria were identified: innovation, demand, usability, functionality, ease of use, risk related to the use of a given gerontechnology, and social and ethical aspects. The criteria were developed in the form of questions. 30 criteria were identified with six questions related to the functionality of the technology (TF1–TF6), five — to technological innovation (TI1–TI5) and demand for the technology (TD1–TD5), four — to social and ethical aspects (SEC1–SEC4), and four — to the risk of using the technology (TUR1–TUR4). Lastly, three criteria were associated with the usability of the technology (TU1–TU3) and ease of use (TEU1–TEU3). The list of criteria used in the assessment of gerontechnologies in Poland is presented in Table 1.

The respondents assessed the G1 using each criterion. They had to determine to what extent the use of G1 would contribute to the fulfilment of a criterion. A 9-point score was used for the evaluation, where one meant "to a very small extent", and nine meant "very much". E.g., choosing one for the TI1 criterion meant that the technologies from the G1 group were considered low innovation. On the other hand, choosing nine for the TI2 criterion meant that the application of the G1 technology would greatly improve the quality of the existing care system.

The G1 was initially assessed against the innovation criteria. Most of the respondents (over 55 %) considered that applying this group of technologies to care for older adults was, to a large extent, an innovative solution in demand (TI1). Almost 60 % of the respondents believed that the application of this group of technologies to care for older adults would greatly improve the quality of the existing care system (TI2). Less than half of the respondents stated that the use of this group of technologies to care for older adults was, to a large extent, a breakthrough solution globally (TI3), and over 57 % of the respondents stated that it was a breakthrough solution for Poland (TI4). The vast majority of the respondents stated that this group of technologies could significantly improve the quality of life of older people, and only 7.7 % of the respondents believed that this group of technologies could do little to improve the quality of life of older people (TI5). Detailed data on the technology

Tab. 1. Catalogue of group assessment criteria

Acronym	Name of criterion
Technology innovation	
TI1	To what extent is the use of this group of technologies for the care of older adults an innovative solution in demand?
TI2	To what extent will the application of this group of technologies for the care for older adults significantly improve the quality of the existing care system?
TI3	To what extent is the use of this group of technologies for the care of older adults a breakthrough solution in the world?
TI4	To what extent is the use of this group of technologies for the care of older adults a breakthrough solution in Poland?
TI5	To what extent can the use of this group of technologies for the care of older adults significantly improve the quality of life of older adults?
Technology demand	
TD1	To what extent is there a demand from older people for technologies from this group?
TD2	To what extent is there a demand for this technology from family members for technologies from this group?
TD3	To what extent is the global demand for technologies from this group is related to fashion?
TD4	To what extent will the use of technologies from this group require no new specialised knowledge?
TD5	To what extent will this group of technologies be important for everyday life?
Social and ethical criteria	
SEC1	To what extent will the widespread use of this technology in the care of older adults bring measurable social benefits?
SEC2	To what extent will the widespread use of this technology in the care of older adults create new jobs?
SEC3	To what extent will the widespread use of this technology in the care of older adults bring measurable benefits for human health and quality of life?
SEC4	To what extent can the widespread use of technologies in the care of older adults be a source of social problems?
Technology usability	
TU1	To what extent will the use of technologies from this group improve the quality of care services for older adults?
TU2	To what extent will the use of this technology for the care of older adults improve their safety?
TU3	To what extent will the use of this technology for the care of older adults contribute to spending time pleasantly and enjoyably?
Technology functionality	
TF1	To what extent will the technologies in this group mean that older adults have to do no heavy work?
TF2	To what extent will the functionality of the technologies in this group enable interaction?
TF3	To what extent will the functionality of the technologies in this group enable older adults to inform their loved ones about their health?
TF4	To what extent will the functionality of the technologies in this group make it possible to call for help for older adults?
TF5	To what extent will the functionality of this group of technologies make the movement of older people easier and more efficient?
TF6	To what extent will the use of the technologies from this group improve the everyday life of older adults?
Technology ease of use	
TEU1	To what extent does the use of the technologies from this group require breaking down mental barriers?
TEU2	To what extent should the use of this technology be easy and intuitive?
TEU3	To what extent would you find it difficult to learn to use this technology?
Technology use risk	
TUR1	To what extent can the use of this group of technologies for the care of older adults be a source of danger?
TUR2	To what extent can the use of this group of technologies for the care of older adults expose users to a loss of health or life?
TUR3	To what extent can the technologies in this group pose a threat to human relationships?
TUR4	To what extent would you be able to trust the technologies in this group?

innovation criterion for the "Health" group is presented in Fig. 1.

Another considered criterion was "Technology Demand". More than half of the respondents stated a significant demand for technologies from this group for older adults (TD1), and almost 61 % of the respondents believed in a significant demand for these technologies from family members (TD2). More than 43 % of the respondents believed that the global demand for technologies in this group was to a medium extent related to fashion, and almost 33 % did not believe that this phenomenon was temporary (TD3). More than 20 % of the respondents said that the use of these technologies would require older adults to acquire specialised knowledge (TD4). The majority of the respondents said the appearance of the technologies would be important for using them daily (TD5). Detailed data on the criterion of demand for technologies for the "Health" group are presented in Fig. 2.

Social and ethical criteria were examined next (Fig. 3). The vast majority of respondents expressed that using technologies from this group would bring measurable social benefits. Almost 44 % of the respondents claimed that using this group of technologies would contribute to the creation of new jobs to an average extent (SEC2). 57 % of the respondents stated that using technologies from this group would bring measurable benefits for human health and the quality of human life (SEC3). Over 22 % of the respondents said that the widespread use of these technologies might be a minor source of social problems (SEC4).

The respondents were asked to rate the group of technologies in terms of usability (Fig. 4). The vast majority of respondents agree that technologies from this group would improve the quality of care services for older adults (TU1). Over 58 % of the respondents claimed that using technologies from this group would improve the safety of older people (TU2). Less

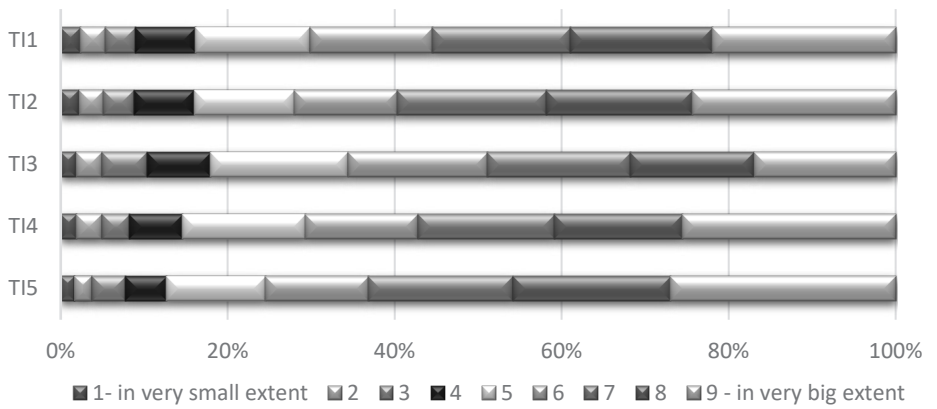

Fig. 1. "Health" gerontechnology group assessment in terms of the Technology Innovation criteria

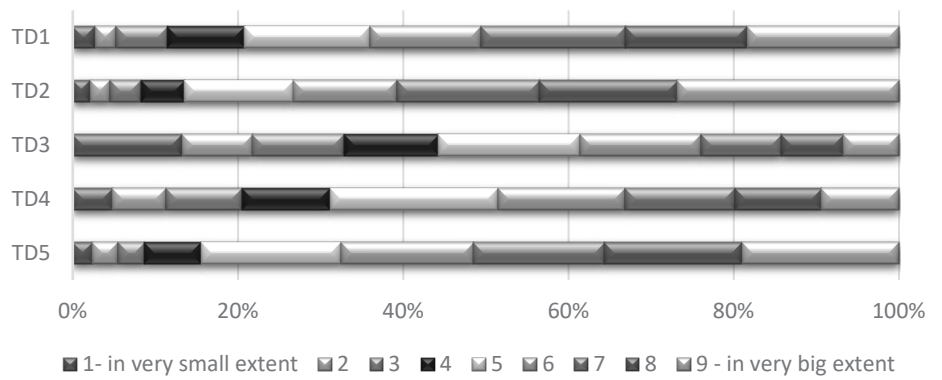

Fig. 2. "Health" gerontechnology group assessment in terms of the Technology Demand criteria

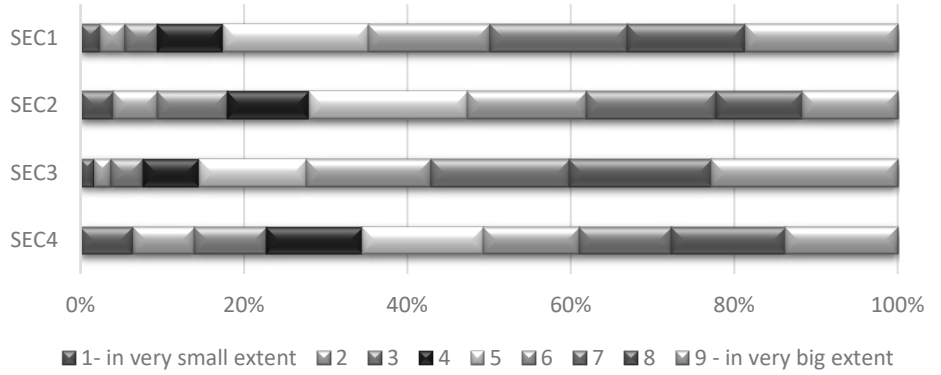

Fig. 3. "Health" gerontechnology group assessment in terms of the Social and Ethical criteria

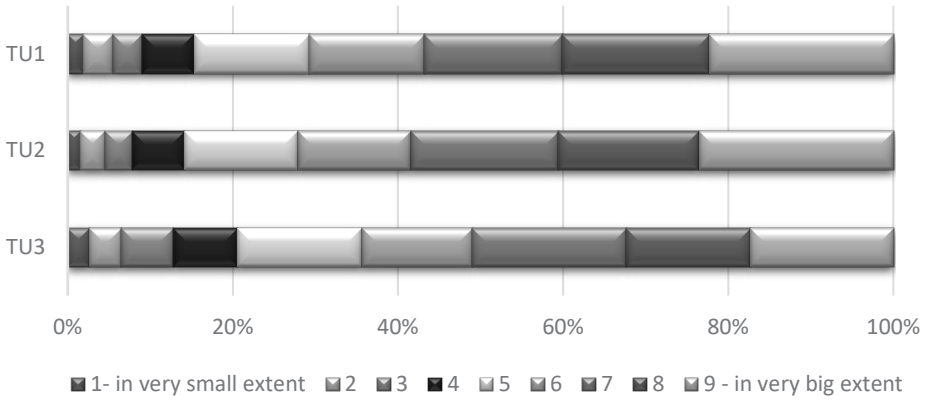

Fig. 4. "Health" gerontechnology group assessment in terms of the Technology Usability criteria

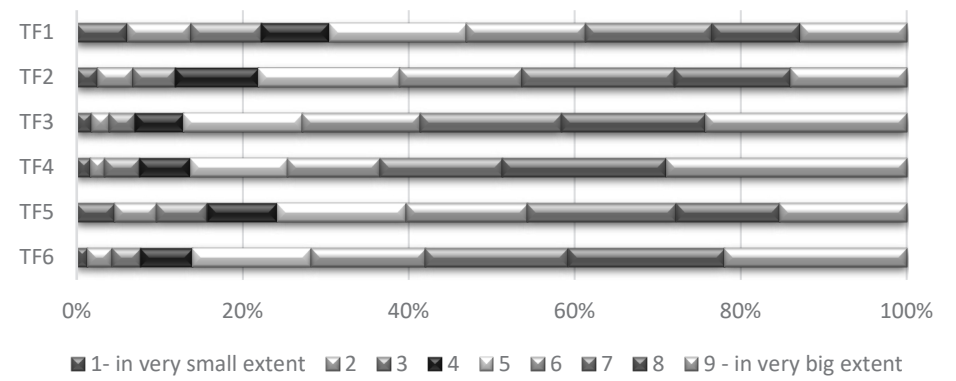

Fig. 5. "Health" gerontechnology group assessment in terms of the Technology Functionality criteria

than 13 % of the respondents stated that using technologies from this group would have little contribution to time spent pleasantly by older adults (TU3).

The next step was to evaluate the groups of technologies for functionality (Fig. 5). Almost 39 % of the respondents claimed that primarily due to technologies from this group, older adults would no longer have to engage in difficult activities (TF1). The vast majority of the respondents (88.2 %) agreed that the functionalities of technologies from this group would

make interactions possible (TF2). Over 58 % of the respondents answered that the functionality of the technologies from this group would make it possible, to a large extent, to inform loved ones about the health of older adults (TF3). Only 7.6 % of the respondents claimed that these technologies would hardly make it possible to call help for older adults (TF4). A large proportion of the respondents (45.7 %) replied that the technologies from this group would make the movement of older adults much easier and more efficient (TF5). Over 90 % of the respondents agreed with the statement that these technologies would improve the daily functioning of older people (TF6).

The respondents also rated health-related technologies for ease of use (Fig. 6). Over 41 % of the respondents answered that using technologies from this group to an average extent would require breaking mental barriers (TEU1). The vast majority of the respondents (54.5 %) agreed that using the technologies from this group should be easy and intuitive (TEU2). Over 40 % of the respondents answered that learning to use the technologies from this group would be a little difficult for them (TEU3).

The last criterion analysed was related to the risk of using the technology (Fig. 7). Nearly 45 % of the respondents stated that using the technologies from this group might largely be a source of risks (TUR1). Less than 50 % of the respondents considered that using these technologies for older adults may largely expose users to a loss of health or life (TUR2). More than 16 % of the respondents answered that the technologies from this group, to a small extent, might pose a threat to human relations (TUR3). 47 % of the

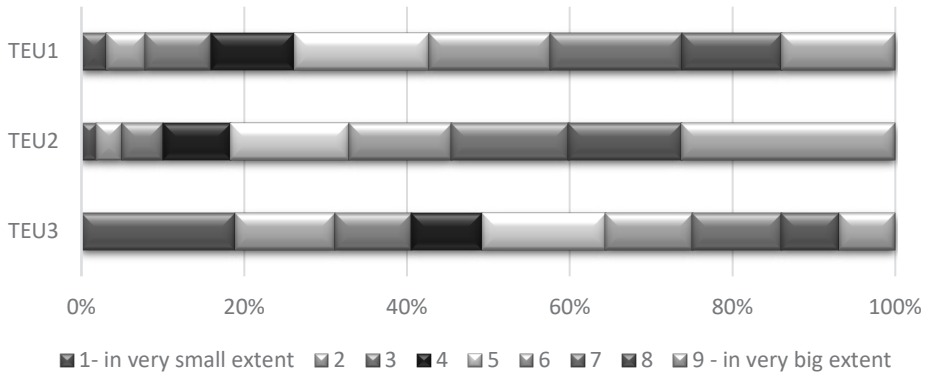

Fig. 6. "Health" gerontechnology group assessment in terms of the Technology Ease of Use criteria

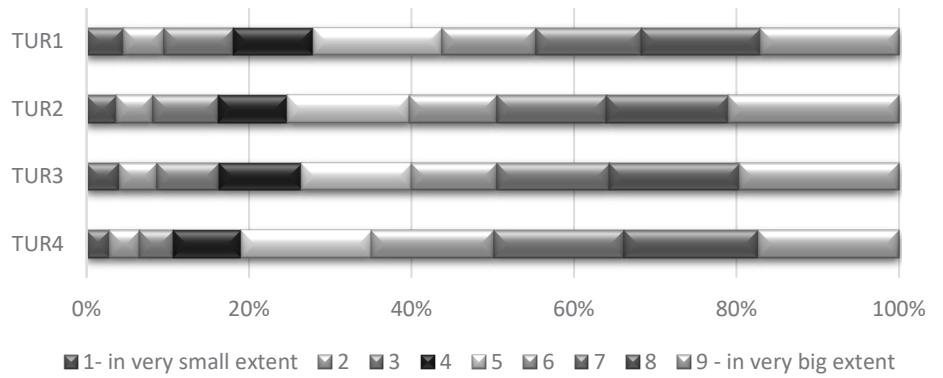

Fig. 7. "Health" gerontechnology group assessment in terms of the Technology Use Risk criteria

respondents stated that they would be able to trust this group of technologies to a medium degree.

4. Discussion of the results

A summary of average ratings given by the gerontechnology respondents from the G1 group (health) for each criterion is presented in Fig. 8. The figure shows arithmetic averages of the respondents' marks for each criterion. E.g., the opinion average for the gerontechnology respondents from the health group regarding the use risk was 6.10, and for usability — 6.49. The maximum value of technology evaluation was nine, and the minimum value was one. Based on the figure, G1 was ranked the highest for innovation (6.60) and lowest for ease of use (5.61).

A more detailed list of the average assessments for G1 gerontechnology depending on a specific criterion is presented in Table 2. Based on the data, G1 technologies were rated the lowest for the TEU3 criterion, which means that learning to use technologies from this group would not be difficult. On the other hand, the highest assessments were given to technologies improving the quality of life for older people in terms of the TF4 criterion, which shows the importance of the functionality to call for help by an older person. Considering innovation (TI), G1 technologies were rated the highest for the criterion TI5 (significantly improve the quality of life of older adults) and the lowest for the criterion TI3 (a breakthrough solution globally). In terms of demand, G1 was rated the highest for TD2 (demand for technology by family members supporting older adults) and the lowest for TD3 (global demand for technologies supporting older adults related to fashion). This shows a very high demand for technologies from this group, while the global demand for technologies from this group is not related to fashion. In terms of functionality, G1 has the highest rating for TF4 (making it possible to call for help for older adults) and the lowest for TF1. Therefore, according to the respondents, technologies from this group would be useful to call for help for

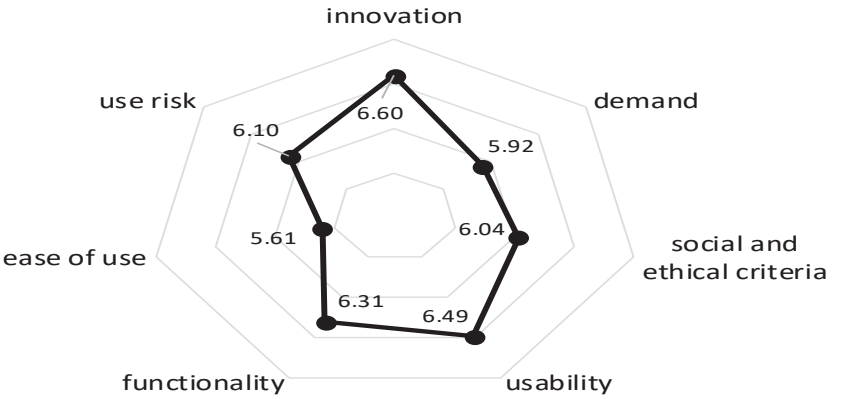

Fig. 8. Average of gerontechnology assessments of the Health group in terms of different groups of criteria

Tab. 2. Average assessment of gerontechnology G1 depending on each of the identified criteria

Acronym of criterion	Average assessment	Acronym of criterion	Average assessment	Acronym of criterion	Average assessment
TI1	6.54	SEC1	6.32	TEU1	5.87
TI2	6.66	SEC2	5.65	TEU2	6.53
TI3	6.28	SEC3	6.65	**TEU3**	**4.42**
TI4	6.65	SEC4	5.53	TUR1	5.90
TI5	6.86	TF1	5.56	TUR2	6.14
TD1	6.26	TF2	6.06	TUR3	6.09
TD2	6.76	TF3	6.72	TUR4	6.27
TD3	4.71	**TF4**	**6.90**	TU1	6.58
TD4	5.43	TF5	5.95	TU2	6.67
TD5	6.42	TF6	6.65	TU3	6.22

older adults. Analysing the social and ethical aspects, G1 was rated the highest in terms of the SEC3 criterion, which means that technologies from this group would bring measurable benefits for human health and the quality of life. In terms of socio-ethical aspects, technologies from this group received the lowest ranking for the SEC4 criterion, which means that technologies from this group should not be the source of social problems.

Conclusions

The article assesses various technologies that improve the quality of life of older people. The research mainly aimed to find answers to the following questions: (1) What is the ranking of gerontechnology groups, and which of the nine gerontechnology groups is most desired by current and future users? (2) What are the individual assessments of future and current users of the most desirable gerontechnology depending on the type of criterion? (3) For which criterion has the selected, most desirable group of gerontechnology been rated the highest?

The conducted research helped to determine that technologies improving the quality of life of older adult related to health were rated the highest (G1 Health Group — the first place in the ranking). Among the most popular technologies in this group were a video chat with a doctor, mHealth mobile applications, an electronic medicine dispenser, and a telemedicine wristband. Technologies from this group were rated the highest for innovation (the mean score of 6.60 on a scale from 1 to 9), usability (the mean score of 6.49 on a scale from 1 to 9) and functionality (6.31). The lowest rating was given to this group in terms of ease of use (the mean score of 5.61 on a scale from 1 to 9).

The results demonstrate that the respondents believed learning to use health-related technologies should not be a problem (the lowest obtained mean score was 4.42). The highest rating was given to these technologies in terms of functionality, allowing to call for help for an older adult (the highest average score obtained was 6.90).

The second place in the ranking was given to technologies improving the quality of life of older people in the G4 group — safety, and the third place in G6 — care. The lowest rating was given to gerontechnologies from the G9 group — digital accessibility.

In the future, the authors intend to extend the research to a larger sample and other countries (e.g., the European Union countries) and include other technology assessment criteria, such as Technological Readiness Levels (TRL) or Life Cycle Analysis (S-LCA). In addition, the plan is to use MCGDM (Multiple Criteria Group Decision Making) methods such as TOPIS, SAW, and to research the projection of gerontechnology development in the future, in the perspective of 20–30 years. This will involve the application of foresight methods, which are widely used for the creation of a long-term vision for the development of countries, cities, technologies, enterprises and various institutions (Nazarko et al., 2017; Ejdys et al., 2019; Szpilko, 2020; Nazarko et al., 2019).

Acknowledgements

This research was funded by the Ministry of Science and Higher Education, grant number W/WIZ/1/2019 and W/WIZ/9/2020.

The publication of the article for 11th International Conference on Engineering, Project, and Production Management - EPPM2021 was financed in the framework of the contract no. DNK/SN/465770/2020 by the Ministry of Science and Higher Education within the "Excellent Science" programme.

Literature

Assisted Living. Top 25 smartphones for Seniors. Retrieved from https://assistedlivingtoday.com/blog/best-smartphones-for-seniors/

Batsis J. A., Zagaria, A., Kotz, D. F., Bartels, S. J., Boateng, G. G., Proctor, P. O., Halter, R. J., & Carpenter-Song, E. A. (2018). Usability evaluation for the Amulet Wearable Device in rural older adults with obesity. *Gerontechnology*, *17*(3), 151-159. doi: 10.4017/gt.2018.17.3.003.00

Bernard, M., Liao, C. H., & Mills, M. (2001). The effects of font type and size on the legibility and reading time of online text by older adults. Paper presented at the CHI'01 extended abstracts on Human factors in computing systems.

Bixter, M. T., Blocker, K. A., Mitzner, T. L., Prakash, A., & Rogers, W. A. (2019). Understanding the use and non-use of social communication technologies by older adults: A qualitative test and extension of the

UTAUT model, *Gerontechnology*, *18*(2), 70-88. doi: 10.4017/gt.2019.18.2.002.00

Bojanić, I. B., & Erceg, A. (2017). Silver Economy: Demographic change and economic opportunity, Economic Development, Technological Change and Growth. Interdisciplinary Management Research Conference XIII, Croatia, Opatija.

Boruta, M. (2017). Gerontechnologia jako narzędzie w procesie zaspokajania potrzeb mieszkaniowych seniorów [Gerontechnology in providing for the housing needs of the elderly]. *Progress in Economic Sciences*, 4, 25-36. doi: 10.14595/PES/04/002

Bouma, H. (1992). Gerontechnology: Making technology relevant for the elderly. In H. Bouma & J. A. M. Graafmans (Eds.), *Gerontechnology* (pp. 1-5). Amsterdam, Netherlands: IOS Press.

Brossoie, N. (2018). *Social Gerontology, Chapter 2*. Jones and Bartlett Publishers.

Care-O-bot. Retrieved from https://www.care-o-bot.de/en/care-o-bot-4.html

Central Statistic Office Poland. (2020). Ludność. Stan i struktura ludności oraz ruch naturalny w przekroju terytorialnym w 2020 r. [Population. Population status and structure and natural movement in territorial section in 2020]. Retrieved from https://stat.gov.pl/obszary-tematyczne/ludnosc/ludnosc/ludnosc-stan-i-struktura-ludnosci-oraz-ruch-naturalny-w-przekroju-terytorialnym-stan-w-dniu-30-06-2020,6,28.html

Central Statistics Office Poland. (2020). Ludność. Stan i struktura ludności oraz ruch naturalny w przekroju terytorialnym [Population. Population status and structure and natural movement in territorial section]. Retrieved from https://stat.gov.pl/obszary-tematyczne/ludnosc/ludnosc/ludnosc-stan-i-struktura-ludnosci-oraz-ruch-naturalny-w-przekroju-terytorialnym-stan-w-dniu-31-12-2019,6,27.html

Cursaru, A. (2018). *Main Causes of Population Aging and its Consequences on the provision of Healthcare*. ECON322.

Dahmen, J., Minor, B., Cook, D., Vo, T., & Schmitter-Edgecombe, M. (2018). Smart home-driven digital memory notebook support of activity self-management for older adults. *Gerontechnology*, *17*(2), 113-125. doi: 10.4017/gt.2018.17.2.005.00

Ejdys, J. (2018). Building technology trust in ICT application at a University. *International Journal of Emerging Markets*, *13*(5), 980-997. doi: 10.1108/IJoEM-07-2017-0234

Ejdys, J., & Halicka, K. (2018). Sustainable Adaptation of New Technology – The Case of Humanoids Used for the Care of Older Adults. *Sustainability*, *10*(10), 3770. doi: 10.3390/su10103770

Ejdys, J., Gudanowska, A., Halicka, K., Kononiuk, A., Magruk, A., Nazarko, J., Nazarko, Ł., Szpilko, D., & Widelska, U. (2019). Foresight in Higher Education Institutions: Evidence from Poland. *Foresight and STI Governance*, *13*, 77-89. doi: 10.17323/2500-2597.2019.1.77.89

European Commission. (2015). Growing the European Silver Economy – Background paper. Retrieved from http://ec.europa.eu/research/innovation-union/pdf/active-healthy-ageing/ silvereco.pdf

European Union Publications Office. (2018). The Silver Economy: Final Report 2018, Retrieved from https://op.europa.eu/pl/publication-detail/-/publication/a9efa929-3ec7-11e8-b5fe-01aa75ed71a1

Halicka, K. (2019). Gerontechnology — the assessment of one selected technology improving the quality of life of older adults. *Engineering Management in Production and Services*, *11*(2), 43-51. doi: 10.2478/emj-2019-0010

Halicka, K. (2020). Technology Selection Using the TOPSIS Method. *Foresight and STI Governance*, *14*(1), 85-96. doi: 10.17323/2500-2597.2020.1.85.96

Halicka, K., & Surel, D. (2020). Evaluation and Selection of Technologies Improving the Quality of Life of Older People, *European. Research Studies Journal*, *23*(2), 592-611. doi: 10.35808/ersj/1611

Hsieh, K. L., Fanning, J. T., & Sosnoff, J. J. (2019). A smartphone fall risk application is valid and reliable in older adults during real-world testing. *Gerontechnology*, *18*(1), 29-35. doi: 10.4017/gt.2019.18.1.003.00

Hsieh, K. L., Fanning, J. T., Rogers, W. A., Wood, T. A., & Sosnoff, J. J. (2018). A fall risk mHealth app for older adults: Development and usability study. *JMIR Aging*, *1*(2), e11569. doi: 10.2196/11569

Hsu, Y., & Li Bai, D. (2016). The Future of Gerontechnology: Proposals from the new editor-in-chief. *Gerontechnology*, *15*(3), 125-129.

Jarocka, M., & Wang, H. (2018). Definition and classification criteria of logistics services for elderly. *Engineering Management in Production and Services*, *10*(4), 65-75.

Klimczuk, A. (2011). Transfer technologii w kształtowaniu srebrnej gospodarki [Technology transfer in shaping the silver economy]. In M. Grzybowski (Ed.), *Transfer wiedzy w ekonomii i zarządzaniu* [*Knowledge transfer in economics and management*], (pp. 57-75). Gdynia, Poland: Wydawnictwo Uczelniane Akademii Morskiej w Gdyni.

Klimczuk, A. (2016). Modele srebrnej gospodarki w UE w ujęciu porównawczym. Próba wprowadzenia do dyskusji [Models of the silver economy in the EU in a comparative approach. An attempt to introduce you to the discussion]. *Problemy Zarządzania*, *14*(2), 41-59.

Nap, H. H., Diaz-Orueta, U., González, M. F., Lozar-Manfreda, K., Facal, D., Dolničar, V., Oyarzun, D., Ranga, M. M., & de Schutter, B. (2014). Older people's perceptions and experiences of a digital learning game. *Gerontechnology*, *13*(3), 322-331. doi: 10.4017/gt.2015.13.3.002.00

Nazarko, J., Ejdys, J., Halicka, K., Nazarko, Ł., Kononiuk A., & Olszewska, A. (2017). Structural Analysis as an Instrument for Identification of Critical Drivers of Technology Development. *Procedia Engineering*, *182*, 504-509. doi: 10.1016/j.proeng.2017.03.137

Nazarko, Ł., & Melnikas, B. (2019). Responsible Research and Innovation in Engineering and Technology Management: Concept, Metrics and Assessment. IEEE Technology & Engineering Management Con-

ference (TEMSCON). Retrieved from https://ieeexplore.ieee.org/document/8813596

Oxford Economics. (2013). The Longevity Economy. Generating economic growth and new opportunities for business. Retrieved from https://www.aarp.org/content/dam/aarp/home-and-family/personal-technology/2013-10/Longevity-Economy-Generating-New-Growth-AARP.pdf

RoboticsBIZ. Top seven companion and social robots for elderly people. Retrieved from https://roboticsbiz.com/top-seven-companion-and-social-robots-for-elderly-people/

Rzeczynski, B. (2009). Gerontechnologia w przestrzeni komunalnej [Gerontechnology in communal space]. *Przegląd Komunalny*, *3*, 86-87.

Sale, P. (2018). Gerontechnology, Domotics and Robotics. In S. Masiero & U. Carraro (Eds.), *Rehabilitation Medicine for elderly patients* (pp. 161-169). Springer International Publishing. doi:10.1007/978-3-319-57406-6

Simsik, D. (2012). The Mechatronic Shoe: A new Rehabilitation, 29th International Symposium on Automation and Robotics in Construction. 8th World Conference of the International Society for Gerontechnology. doi: 10.22260/ISARC2012/0070

Szpilko, D. (2020). Foresight as a tool for the planning and implementation of visions for smart city development. *Energies*, *13*(7), 1782. doi: 10.3390/en13071782

Tellier, M., Auger, C., Bier, N., & Demers, L. (2020). Use of an electronic pillbox by older adults with mild Alzheimer's disease: Impact on medication administration and adherence. *Gerontechnology*, *19*(1), 66-76. doi: 10.4017/gt.2020.19.1.007.00

United Nations. (2019). Word Population Ageing 2019 Highlights. Retrieved from https://www.un.org/en/development/desa/population/publications/pdf/ageing/WorldPopulationAgeing2019-Report.pdf

Wieczorek, A. (2016). Gerontechnologia w rozwiązywaniu problemów osób starszych [Gerontechnology in solving problems of the elderly]. *Systemy Wspomagania w Inżynierii Produkcji*, *2*(14), 358-370.

Zimnoch, K. (2013). Starzenie się i srebrna gospodarka w uwarunkowaniach rozwojowych Podlasia [Aging and the silver economy in the development conditions of Podlasie]. *Optimum. Studia Ekonomiczne*, *4*(64), 25-36.

sciendo

ISMSME International Society for Manufacturing, Service and Management Engineering

received: 1 April 2021
accepted: 31 August 2021

pages: 127-141

Partial replacement of cement with rice husk ash in concrete production: an exploratory cost-benefit analysis for low-income communities

Franco Muleya Natasha Muwila
Chipozya Kosta Tembo Alice Lungu

ABSTRACT
Cement is an important construction material in concrete production; however, it is expensive and unaffordable for many low-income and rural communities in developing countries. Rice husk is a by-product from the rice mill process, with an approximate ratio of 200 kg rice husk per one tonne of rice produced. This experimental study aimed to investigate the integrity of concrete produced in Zambia using rice husk ash (RHA) to partially replace cement. The primary goal was to carry out a cost–benefit analysis on the use of RHA in concrete. RHA was used to partially replace cement with ratios of 10 %, 20 % and 30 %. The 20 % cement replacement mix produced the optimum 18 MPa concrete strength results at a 0.5 water/binder ratio. This translated in cost reduction of concrete by 12.5 %, which is particularly significant for higher concrete volumes. The produced concrete is suitable for lightly loaded structures, such as foundation footings, surface beds and walkways to benefit low-income communities. The study further concluded that the RHA based concrete was more cost-efficient in structures that were close to areas of rice production due to reduced RHA transportation costs.

KEY WORDS
rice husk ash, partial replacement, concrete, cost reduction

10.2478/emj-2021-0026

Franco Muleya

The Copperbelt University, Zambia
ORCID 0000-0002-3552-6198

Corresponding author:
email: muleyaf@yahoo.co.uk

Natasha Muwila

Adam Hood Consulting, Zambia
ORCID 0000-0003-2352-6120

Chipozya Kosta Tembo

The Copperbelt University, Zambia
ORCID 0000-0001-5195-0821

Alice Lungu

The Copperbelt University, Zambia
ORCID 0000-0002-7963-9856

Introduction

The construction industry has experienced major innovations in concrete production methods alternative to conventional concrete. Naik (2008) states that when applied correctly, concrete production innovations encourage sustainability, reduce project delivery time, improve on-site waste management, and reduce the total construction cost. According to Singh (2008), sustainability has become a worldwide goal. Green or sustainable buildings use key resources like

Muleya, F., Muwila, N., Tembo, Ch. K., & Lungu, A. (2021). Partial replacement of cement with rice husk ash in concrete production: an exploratory cost–benefit analysis for low-income communities. *Engineering Management in Production and Services, 13*(3), 127-141. doi: 10.2478/emj-2021-0026

energy, water, minerals and land much more efficiently than those merely built according to codes. Fapohunda et al. (2017) state that global warming triggered by the emission of greenhouse gases, such as carbon dioxide (CO2), into the atmosphere can be reduced by replacing gas-emitting materials. One of these substitute materials is rice husk ash (RHA), which has been established as a suitable material for the partial replacement of portland cement in concrete production. Alam (2015) states that rice husk is not recommended for human consumption because of its less nutritional content and its irregular abrasive surfaces, which are not naturally degraded, thereby presenting the potential to cause serious health-related problems. Many studies have been conducted on the use of rice husk for many decades and have proved that one tonne of rice produces 200 kg of rice husk, which translates into 40 kg of ash. This represents 20 % of husk and 4 % of ash (Zareei, 2017; Bui, 2001; Fapohunda et al., 2017).

1. Background

According to the Second National Rice Development Strategy (2016 – 2020), the SNRDS (2016), Zambia had been on average producing about 44 512 metric tonnes of paddy rice (approx. 29 000 metric tonnes in milled rice) annually between 2010 and 2016. However, a deficit in production resulted from consumption plateauing at 60 000 metric tonnes (approx. 39 000 metric tonnes in milled rice). Paddy rice is rice covered by husks. During the same six-year timeframe (2010 – 2016), the SNRDS (2016) reported that Zambia had a rice deficit resulting in the importation of between 5 000 and 20 000 metric tonnes of milled rice annually to meet domestic demand. Zambia's failure to produce rice to meet local demand was mainly attributed to limited access to improved varieties and quality seed, poor farming practices, poor water management system, low level of mechanisation, inadequate human and institutional capacity and limited access to seasonal and long-term finance.

The SNRDS (2016) further shows that rice production occurred in different regions, including Lusaka, Central and Copperbelt provinces considered rural or remote from the main economic activity centres. The report underpinned by the Ministry of Agriculture states that rice is produced in ten of the eleven Zambian provinces (Table 1). Table 2 shows a breakdown of average rice production by province, showing an average of 44 512 metric tonnes for the whole country in the period 2010 – 2016. Table 2 further indicates that most rice production occurs in rural provinces, such as Eastern, Luapula, Muchinga, Northern and Western. The provinces and their rice fields are home to many households with compromised infrastructure, which could be improved with the provision of cheaper concrete based on rice husk — the material currently treated as waste. Fig. 1 shows the most recent recorded yet lower rice production levels in Zambia at 29 584 metric tonnes in 2019. Based on the rice husk production levels amounting to 20 % of rice production, the estimated produced husk was 5 917 tonnes, translating into 1 183 tonnes of rice husk ash. Further, Fig. 1 shows that rice production began to significantly increase in 2008, resulting in a corresponding increase in rice husk and ash at the time. Currently, no documented information is available on established cost–benefit analysis on the use of rice husk ash to partially substitute portland cement in Zambia. As a result, this research set out to determine the properties exhibited by concrete produced using Zambian RHA and to carry out a cost–benefit analysis of this concrete. Lit-

Tab. 1. Key features of rice production in Zambia between 2010 and 2016

Province	Percentage of rice production hectarage covering 38 537 hectares [%]
Western Province	46
Northern Province	32
Muchinga Province	13
Luapula Province	4
Eastern Province	4
Other provinces, namely: Central, Southern, Copperbelt, Northwestern and Lusaka	1

Source: (SNRDS, 2016).

Tab. 2. Basic rice data by region in Zambia (average 2010/11 to 2014/15)

Provinces	Number of households growing	Area planted (ha)	Area harvested (ha)	Production (MT)	Yield (MT/ha)	Average rice plot size per household
Central	177	72	66	129	1.38	0.41
Copperbelt	93	25	23	33	1.46	0.27
Eastern	5 385	1 581	1472	2437	1.55	0.29
Luapula	5 570	1 569	1390	2731	1.78	0.28
Lusaka	164	50	42	64	1.06	0.31
Muchinga	13 020	4 823	4513	7931	1.66	0.37
Northern	15 893	12 413	11315	16182	1.31	0.78
Northwestern	1 096	345	315	509	1.51	0.31
Southern	109	37	28	17	0.26	0.33
Western	26 542	17 622	9038	14479	0.90	0.66
National	68 051	38 537	28202	44512	1.16	0.57

Source: SNRDS, 2016.

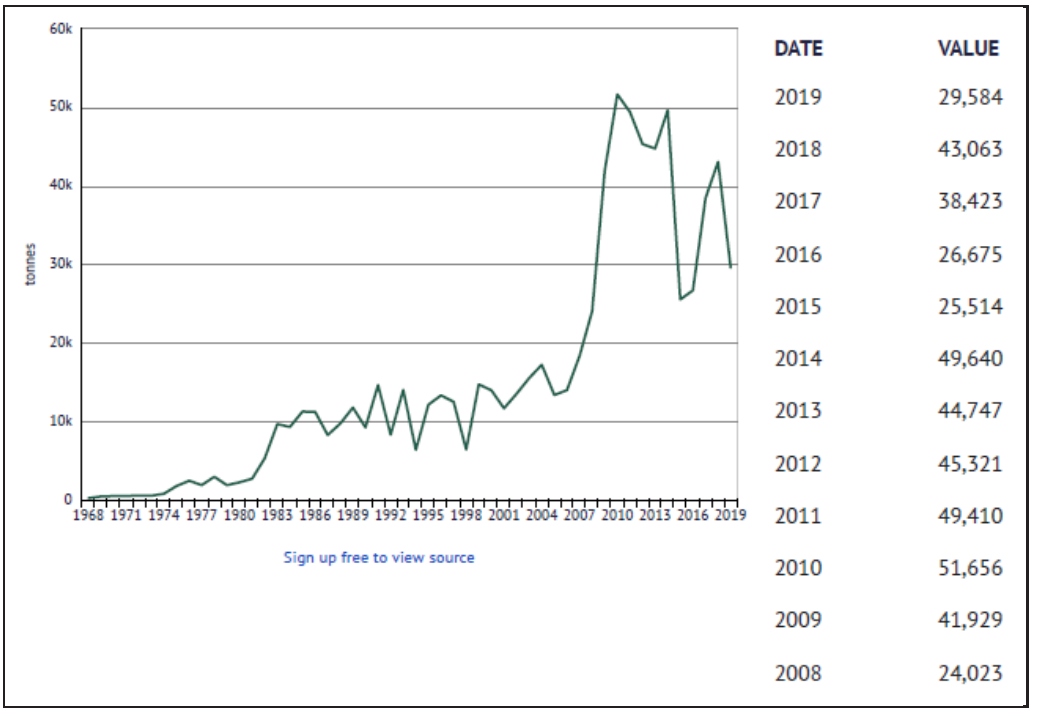

Fig. 1. Zambia's rice production from 1978 to 2019

Source: https://knoema.com/atlas/Zambia/topics/Agriculture/Crops-Production-Quantity-tonnes/Rice-paddy-production.

erature indicates that much of the studies on this subject have concentrated on the feasibility of attaining functional RHA-based concrete and its properties.

Particularly in Zambia, the cost-effectiveness of using this type of concrete has not been addressed. The study was therefore positioned to investigate the functionality and cost-effectiveness of using RHA-based concrete as a measure of reducing the unit cost of concrete using RHA while retaining the structural integrity of the concrete. The functionality of the RHA-based concrete was also considered comparing the performance of local RHA with global patterns through literature review.

The ultimate objective of this paper was to establish the benefits of using RHA in rice-growing rural communities of Zambia (Tables 1 and 2) as a way of bringing down the cost of concrete and improving the infrastructure, mainly developed using unimproved clay. This solution would eventually improve

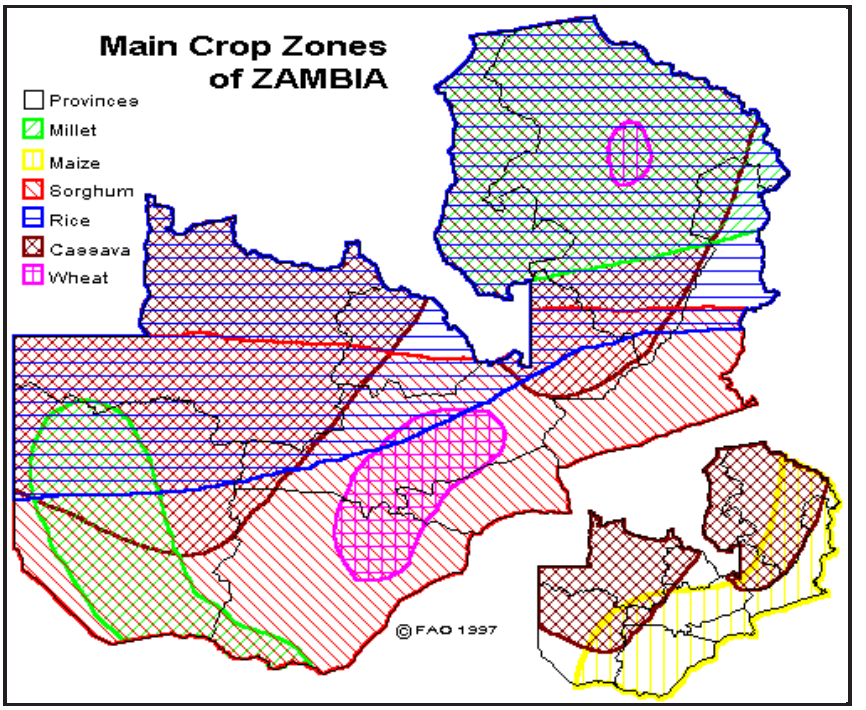

Fig. 2. Map of Zambia showing rice-growing area and provinces as discussed in Background

Source: https://www.pinterest.com/pin/770467448725782191/.

the livelihood and quality of life of rural communities in rice-growing areas. Currently, the produced rice husk goes to waste but could be turned into a useful green construction material resource as already described. Fig. 2 shows the rice-growing area and provinces as discussed in Background.

2. Literature review

As part of the global sustainability agenda to reduce carbon footprint and stay as environmentally friendly as possible, cement and sand replacement materials in concrete exist in various forms, such as blast furnace slag, which is a by-product of iron manufacturing used as a substitute for cement (Pal et al., 2003; Divsholi et al., 2014; Salvador et al., 2019; Ozbay et al., 2016; Mo et al., 2015). Fly ash, a fine powder, which is a by-product of burning pulverised coal in electric generation power plants, has been used to partially replace cement and sand in concrete (Christy & Tensing, 2010; Dhaka & Roy, 2015; Muhit et al., 2013; Jatio et al., 2019; Rajamane et al., 2007; Rafieizonooz et al., 2016; Reshma et al., 2021; Rajagopalan, 2019; Podolyakina, 2016; Białas, 2016). Copper tailings have also been used to partially replace sand and cement in concrete to reduce the depletion of natural resources (Muleya et al., 2020; Dandautiya & Singh, 2019; Kundu et al., 2016; Swetha et al., 2015). Environmental benefit analysis has been performed for many of these studies, which indicate significant absorption of waste from dumpsites while reducing the cost of concrete (Muleya et al., 2020).

The use of agricultural residue, particularly rice residue, is not a new concept in the construction industry. It can be dated back to as early as the 1950s, when Egypt adopted several low-cost housing strategies (Allam & Garas, 2010). Loamy Nile mud mixed with straw resulted in strong bricks. A sun-baked mud brick with the addition of rice straw made it three times stronger (Allam & Garas, 2010). Many other studies indicated in the next passage have investigated the performance of rice husk ash as a partial replacement of cement in the production of concrete. A study by Pode (2016) states that rice husk is an agricultural waste abundantly available in rice-producing countries, such as India, Bangladesh, Brazil, China, Cambodia, the USA, Myanmar, Vietnam, and Southeast Asia. Despite attaining large annual production levels of rice worldwide, RH has only been recycled for low-value applications. Siddika et al. (2020) and Thiedeitz et al. (2020) affirms that rice husk ash (RHA) is a good supplementary cementitious material for concrete production because of its low energy demand and negligible greenhouse gas emission in addition to high pozzolanic reactivity.

Further, the study concluded that RHA had demonstrated its ability to improve concrete strength and durability properties, in addition to the reduced construction and carbon emissions.

2.1. Chemical constituents and properties of Rice Husk Ash

The study of the RHA chemical composition is one of the most important parts because it provides clues on the behaviour of RHA. Table 3 shows a summary and average values of the chemical composition of RHA as presented by Fapohunda et al. (2017), derived from 30 different studies by 30 different authors from 1992 to 2016. Table 3 shows that silica (SiO2) was the most dominant of all oxides in RHA, with the lowest value of 73.60 % and the highest — 97.53 %. The average for the 30 studies was 87.9 %. Further, the total sum of silica, alumina and iron oxide (SAF) (Table 3) also exceeds 70 %, averaging 89.05 in the 30 studies as shown in Table 3. All the RHA specimens demonstrated that the RHA belongs to the same category as the Class F fly ash. Research results by Siddika et al. (2020) were consistent with findings by Fapohunda et al. (2017) on the oxide content of RHA, which has high pozzolanic characteristics. Table 1 clearly indicates that all research results presented a very high silica content of above 70 %. This is a measure of the RHA reactivity. Silica is the compound responsible for the strength in concrete (Fapohunda et al., 2017).

Tab. 3. Oxide composition of RHA

Constituents	Average percentages based on 30 studies/authors between 1992 to 2016
Silica (SiO_2)	87.90
Alumina (Al_2O_3)	0.69
Iron Oxide (Fe_2O_3)	0.55
Calcium Oxide (CaO)	1.00
magnesium Oxide (MgO)	0.54
Sulphur Oxide (SO_3)	0.34
Sodium Oxide (Na_2O)	0.56
Potassium Oxide (K_2O)	2.26
Loss of Ignition (LOI)	5.52
Total (SAF) SiO_2+Al_2O_3+Fe_2O_3	89.05

Source: (Fapohunda et al., 2017).

Studies in ten countries by various researchers (Muthadhi & Kothandaraman 2007; Joel, 2010; Muthandhi & Kothandaraman, 2010; Oyekan & Kamiyo, 2011) revealed that high content of silica ranges from 67 % to 93.1 % and SAF content from 70 % to 93.52 %. The countries included Brazil, Canada, Guyana, India, Iraq, Japan, Malaysia, Nigeria, Thailand, the USA and Vietnam, indicating a very wide and global span of the studies. It is worth noting that the 30 pieces of research and the research in ten countries harvested the optimal concrete compressive strength from between 10 % and 30 % cement replacement with RHA. These results were consistent with those by Fapohunda et al. (2017). Additionally, there seems to be variedness in the results, making it harder to generalise the study findings without cor-

Tab. 4. Summary of RHA and associated output from various authors

Rice Husk Ash % replacement for cement	0 % RHA (Control mix)		10 % RHA		20 % RHA		30 % RHA	
Authors	Compressive strength (MPa)	Density (kg/m³)	Compressive strength (MPa)	Density (kg/m³)	Compressive strength (MPa)	Density (kg/m³)	Compressive strength (MPa)	Density (kg/m³)
Obilade (2014)	29.15	2430	20.88	2300	18.59	2290	13.29	2280
Al-Khalaf & Yousif (1984)	23.30	-	25.40	-	24.10	-	22.80	-
Ephraim et al. (2012)	N/A	-	22.00	-	20.00	-	19.00	-
Akeke et al. (2013)	N/A	-	22.00	2017	20.00	1950	19.00	19
Krishna et al. (2017)	27.00	-	29.80	-	16.03	-	-	-
Krishna et al. (2015)	39.00	-	40.50	-	-	-	32.50	-
Ahsan & Hossain (2018)	36.10	-	22.80	2323	16.80	23	-	-

responding findings and experiments. The compressive strength of concrete is an important property because it underpins the design of structural concrete and defines compliance as a means of field quality control.

Research by Calica (2008) indicates that a mixture containing RHA requires more water compared to those without it, and the water demand increased with more replacement of the cement by the ash. This is attributed to the porous structure of rice husk, which induces a large surface area. However, the workability or fluidity of the mix can be improved by using a good superplasticiser. Table 4 provides a summary of RHA and associated output from various authors as a way of establishing optimum outputs of partial cement revealment of concrete with RHA. The table shows selected RHA-based concrete showing portland cement replacement by RHA from 10 % to 30 % along with compressive strength and density outputs. The table is consistent with the earlier results of other scholars.

3. Research methods

Research methodology focuses on general laws and principles of arranging the research activity and selecting an efficient, adequate and rational research technique (Novikov & Novikov, 2019). The research took the quantitative approach, which Creswell (2009) defined as the employment of inquiry strategies, such as experiments and surveys. Further, numerical data was collected using predetermined instruments to yield quantifiable data that can be subjected to statistical treatment or analysis. The study was positivist philosophically and, therefore, deductive. The research was mainly driven by experiments underpinned by a literature review on the partial replacement of concrete elements with RHA in concrete production. The experimental stage explored the suitability of RHA as a partial replacement of cement in concrete. Further, the optimum percentage of cement was established that could be replaced by RHA in concrete production. The optimum cement replacement refers to the maximum amount of cement that can be partially replaced by RHA without compromising the concrete's safety, integrity and intended function. Laboratory experiments were used to achieve the aim of the study. Fresh concrete was prepared for carrying out slump and workability tests. Slump and compaction factor tests were used to establish concrete workability and later cast six concrete cubes for each mix to obtain the average values for each mix for quality control purposes. A total of 30 concrete cubes, including trial mixes, were cast and completely immersed in water in a curing tank for 28 days to obtain the estimated maximum strength of the concrete cubes.

The study focused on the final concrete product for end-users as an exploratory study, and, thus, all the concrete cubes were tested at 28 days except for trial cubes which were tested at seven days to check for the rate of concrete strength accumulation. Hallingberg et al. (2018) and Muleya et al. (2020) define exploratory research as a study generating the information required to decide how to proceed with a full-scale effectiveness trial, mainly referred to as the pilot or feasibility stage, to prove the concept at hand. The density tests and compressive strength tests constituted the hardened concrete tests. The compressive strength was determined by using a digital compressive strength testing machine shown in Fig. 9. Results of the fresh and hardened concrete are shown in Tables 5 and 6. The reference or control mix did not have the RHA content while other mixes did, ranging from 10 % as a minimum to 30 % as a maximum cement replacement with RHA, which is consistent with the majority of literature results from the

Fig. 3. Rice husks

Fig. 4. Rice husk ash

review because replacements beyond 30 % of RHA were not sustainable due to weakening concrete compressive strength unless superplasticiser is introduced in correct amounts to counteract fluid and compressive strength deterioration. Isolated analysis was used to establish the optimum percentage of cement replacement with RHA. Muleya et al. (2020) define isolated analysis as the process of holding all variables constant while manipulating one of them to determine its influence and effect on the properties of the whole element. The main criteria for determining the quality of the materials were concrete strength driven by concrete-mix design (Emmitt and Gorse, 2014). In this research, the manipulated variable was RHA, which was added in percentages ranging from 0 – 30 % to obtain values for concrete workability, density and compressive strength. Due to the high-water absorption effect of RHA, as seen in the literature review, two water–cement ratios were selected, namely 0.3 and 0.5, to observe the behaviour of the two mixes under the influence of RHA. The two mixes were used to establish the suitability of RHA as a partial replacement of cement in concrete. According to Le and Ludwig (2016), Van et al. (2018), Sharma (2014) and Kanthe (2021), the introduction of superplasticisers to RHA-based concrete improves concrete fluidity and results in improved concrete compressive strength by different values depending on the type of superplasticiser and the quality or grade of used cement. However, this study did not consider the use of superplasticisers because it was exploratory in nature and designed to address the needs of low-income communities with an extremely budget. Besides, the availability and use of plasticisers in Zambia is still unexplored. A future study with the introduction of superplasticisers and longer curing periods is recommended to resolve this study limitation. Fine aggregate, coarse aggregate and portland cement were secured from credible local sources. RH was obtained from the National Milling Company (NMC), which sources rice from fields across the country. The RH was obtained raw and later brunt in an incinerator at 600 degrees to remove carbon and to grind into ash. The RH was left to burn for two days with no further fuelling. It was then allowed to cool for another 24 hours. A pulverisation machine was used to produce fine RHA particles as a final cement replacement. Figs. 3 and 4 show rice husks and rice husk ash, respectively, as captured from the experimental process for this research.

4. Research results and discussion

The compressive strength test results showed that the mix proportions of aggregates used for both concrete cubes of 0.3 and 0.5 w/c ratio yielded 33 MPa and 25 MPa, respectively, for normal concrete after 28 days. While the compressive strength outcomes appear to be low for the given water–cement ratio, the results are consistent with other research (Muleya et al., 2020; Kunda, 2014; Sharma, 2014; Olafusi & Olutoge, 2012). With compressive strength expected to be around 42 MPa and higher, as seen in some findings (Singh, 2018; Ramezanianpour et al., 2009; Zareei, 2017; Muleya & Nwaubani, 2018), the results of this study demonstrate the need to carry out further trial mixes and investigation of cement quality particularly in developing economies. A study by Muleya (2000) revealed that cement for high-strength performance concrete in pile foundations had to be imported because the local cement could not meet the minimum compressive strength of the concrete-mix design. Table 4 illustrates the changes in compressive strength at different RHA percentages. The incorporation of RHA into the concrete using as little as 10 % for replacement results in a decrease in compressive strength both after seven and 28 days of curing. The RHA mixes did not develop a compressive strength comparable to that of the control mix. A less workable mix yields a less dense cube as compared to the concrete mix, as seen in Table 5. This outcome ensues because of friction between the particles causing them to compact less as compared to a more fluid mix. A 0.5 mix resulted in better water absorption by the rice husk ash resulting in more free water to allow complete mixing of the material fractions. While the results of this study meet the objectives to provide cheaper concrete for low-income communities in rice-growing areas, the introduction of superplasticisers in the RHA-based concrete circumvents the challengers of low concrete fluidity and reduced compressive strength. The superplasticiser-based concrete needs longer curing periods, such as 90 days, to understand its full behaviour and properties. This forms a part of the study limitation for widely used RHA-based concrete beyond low-income community requirements. Table 5 compares the recorded results at different 0 %, 10 %, 20 % and 30 % cement replacement with RHA for the two concrete mixes (0.3 and 0.5) from the main experiments of the study.

Tab. 5. Consolidated laboratory results for 0.3 and 0.5 water–cement ratios

Consolidated laboratory results for concrete with water cement ratio 0.3							
Mix 1 (0% Rice Husk Ash)		Mix 2 (10% Rice Husk Ash)		Mix 3 (20% Rice Husk Ash)			
W/C	0.3	W/C	0.3	W/C	0.3		
Materials		**Materials**		**Materials**			
Cement (Kg)	8.8	Cement (Kg)	7.92	Cement (Kg)	7.04		
Rice Husk Ash (Kg)	0	Rice Husk Ash (Kg)	0.88	Rice Husk Ash (Kg)	1.76		
Sand (Kg)	13.2	Sand (Kg)	13.2	Sand (Kg)	13.2		
Stone (Kg)	26.4	Stone (Kg)	26.4	Stone (Kg)	26.4		
Total water (Kg)	4	Total water (Kg)	4	Total water (Kg)	4		
Results		**Results**		**Results**			
Slump (mm)	30	Slump (mm)	0	Slump (mm)	0		
Compaction Factor	0.77	Compaction Factor	0.74	Compaction Factor	0.73		
Cement (kg/m^3)	400	Cement (kg/m^3)	400	Cement (kg/m^3)	400		
Density compacted concrete (kg/m^3)	2491	Density compacted concrete (kg/m^3)	2391	Density compacted concrete (kg/m^3)	2150		
Concrete compressive strentgh (MPa)	33	Concrete compressive strentgh (MPa)	25	Concrete compressive strentgh (MPa)	16		
Consolidated laboratory results for concrete with water cement ratio 0.5							
Mix 4 (0% Rice Husk Ash)		Mix 5 (10% Rice Husk Ash)		Mix 6 (20% Rice Husk Ash)		Mix 7 (30% Rice Husk Ash)	
W/C	0.5	W/C	0.5	W/C	0.5	W/C	0.5
Materials		**Materials**		**Materials**		**Materials**	
Cement (Kg)	7.74	Cement (Kg)	6.97	Cement (Kg)	6.19	Cement (Kg)	5.42
Rice Husk Ash (Kg)	0	Rice Husk Ash (Kg)	0.77	Rice Husk Ash (Kg)	1.55	Rice Husk Ash (Kg)	2.32
Sand (Kg)	13.2	Sand (Kg)	13.2	Sand (Kg)	13.2	Sand (Kg)	13.2
Stone (Kg)	26.4	Stone (Kg)	26.4	Stone (Kg)	26.4	Stone (Kg)	26.4
Total water (Kg)	4.57	Total water (Kg)	4.57	Total water (Kg)	4.57	Total water (Kg)	4.57
Results		**Results**		**Results**		**Results**	
Slump (mm)	55	Slump (mm)	25	Slump (mm)	15	Slump (mm)	0
Compaction Factor	0.91	Compaction Factor	0.85	Compaction Factor	0.84	Compaction Factor	0.82
Cement (kg/m^3)	270	Cement (kg/m^3)	270	Cement (kg/m^3)	270	Cement (kg/m^3)	270
Density compacted concrete (kg/m^3)	2296	Density compacted concrete (kg/m^3)	2530	Density compacted concrete (kg/m^3)	2536	Density compacted concrete (kg/m^3)	2178
Concrete compressive strentgh (MPa)	25	Concrete compressive strentgh (MPa)	22	Concrete compressive strentgh (MPa)	18	Concrete compressive strentgh (MPa)	14

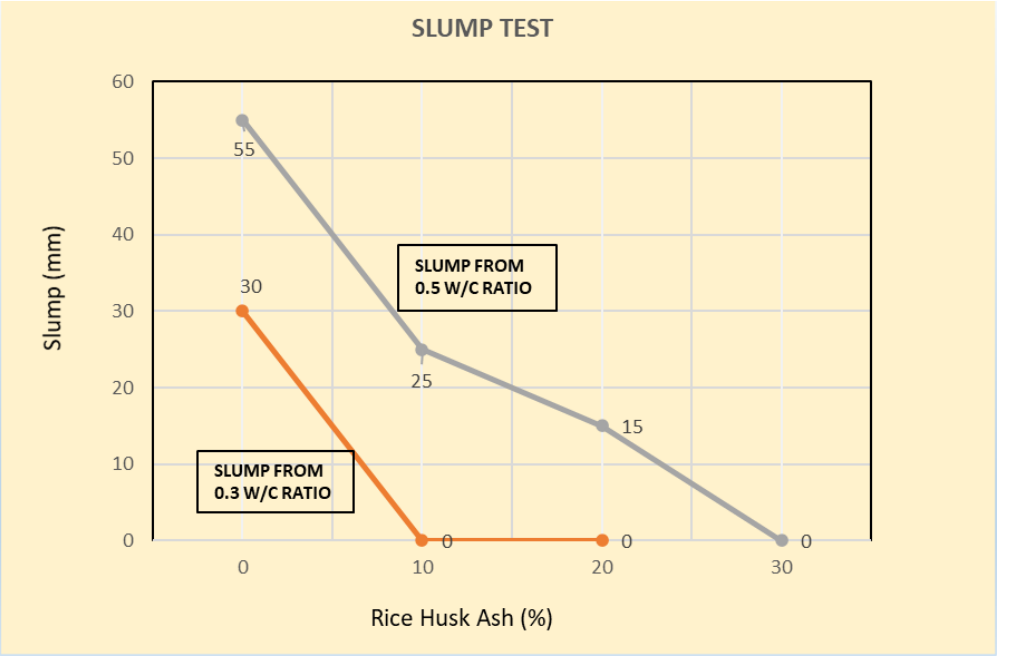

Fig. 5. Slump test showing concrete workability for 0.3 and 0.5 water–cement ratios

Fig. 5 shows the gradual decrease in the slump or workability of the concrete in relation to the increase in the partial replacement of cement with RHA. The results clearly indicate that introduction of RHA results in the decrease of concrete workability. Fig. 6 shows the slump test in progress.

The less fluid concrete mix of 0.3 water–cement ratio got to 0 mm slump faster with a 10 % addition of RHA compared to a more fluid mix of 0.5 water–cement ratio, which got to 0 mm slump with a 20 % and 30 % addition of RHA. The effect of RHA on the slump of fresh concrete is the exact opposite of the effect of copper tailings on partial replacement of sand in concrete, as reported by Muleya et al. (2020). The introduction of copper tailings in concrete results in an increased slump or concrete workability. The replacement of cement with RHA in the 0.3 water–cement ratio only went up to 20 % because the concrete was not fluid beyond that point. In the 0.5 water–cement ratio, concrete fluidity only became impossible beyond 30 % of adding RHA because of the higher water content compared to the 0.3 water ratio mix.

Fig. 7 shows the effect of RHA on the compressive strength of concrete with respect to a gradual increase of RHA in partially replacing cement by up to 30 %. As expected, the 0.3 and 0.5 water–cement ratio mixes without RHA were found to be 33 MPa and 25 MPa, respectively, at 28 days. Results indicated that both water–cement ratio mixes decreased in compressive strength. Figs. 8 and 9 show the hard test process of the concrete strength with the introduction of RHA. Interestingly, at a 20 % replacement of cement by RHA, the 0.5 water cement–ratio mix became stronger than the 0.3 water–cement ratio. At this point, the 0.3 water–cement ratio mix could not be mixed beyond 20 % of RHA addition because the mix was too dry, triggered by the dehydrating effect of RHA on concrete. Beyond 15 % of RHA addition,

Fig. 6. Slump test in progress

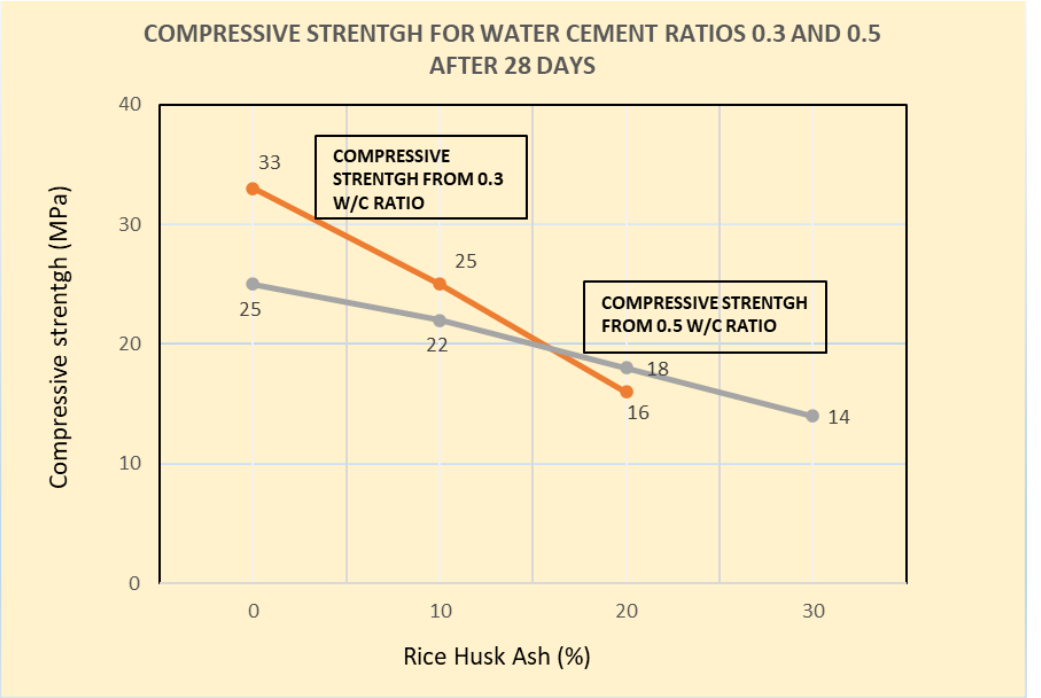

Fig. 7. Compressive strength for 0.3 and 0.5 water–cement ratios

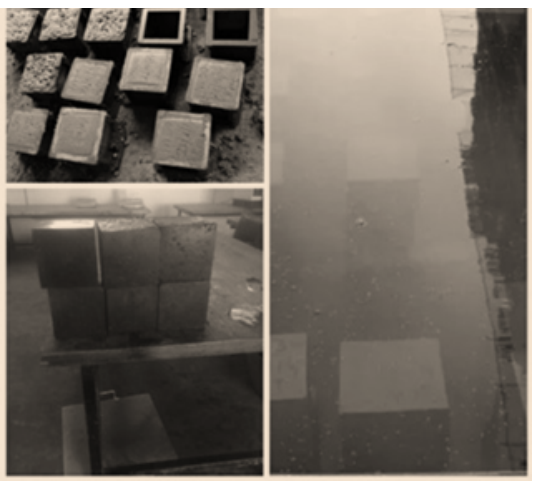

Fig. 8. Concrete cube curing

Fig. 9. Compressive strength testing in progress

the 0.5 water–cement ratio mix became stronger than the 0.3 water–cement ratio, and yet it is the cheaper mix because of the lower cement content. 18 MPa and 14 MPa as lower-strength concrete from 0.5 water–cement ratio mix can be used in various areas of rural communities, such as foundation footings, slabs and crop handling platforms.

4.1. Effect of rice husk ash on concrete density

Fig. 10 shows the concrete density changes for the 0.3 and 0.5 water–cement ratios with respect to increasing partial replacement quantities of cement with RHA. The 0.3 water–cement ratio mix had the highest densities at 0 % and 10 % cement replacement, amounting to 2491 kg/m^3 and 2391 kg/m^3, respectively, while the 0.5 water–cement ratio has its highest densities at 10 % and 20 % cement replacement translating to 2530kg/m^3 and 2536kg/m^3, respectively. The 0.5 water–cement ratio mix had higher densities due to the full compaction because of the adequate water content compared to the less fluid mix influenced by the dehydrating effect of RHA. This result is consistent with that of the compressive strength being higher in the wet mix than the dry mix at a high percentage level of cement replacement with

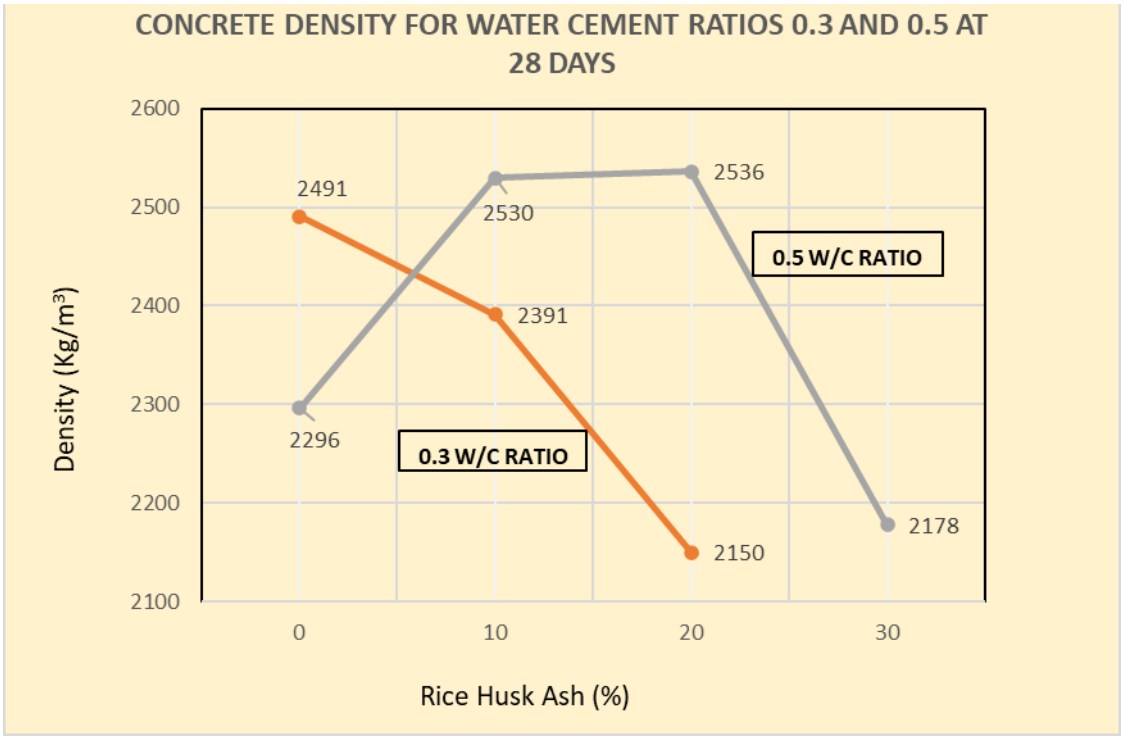

Fig. 10. Concrete density for 0.3 and 0.5 water cement ratios

RHA. These results strongly indicate that higher replacement quantities of cement with RHA is best suited for the more fluid mix of 0.5 water–cement ratio. This result is true for the compressive strength and the density of the concrete.

4.2. Cost–benefit analysis of rice husk ash-based concrete

Fig. 11 indicates the cost savings of concrete based on the partial replacement of cement with

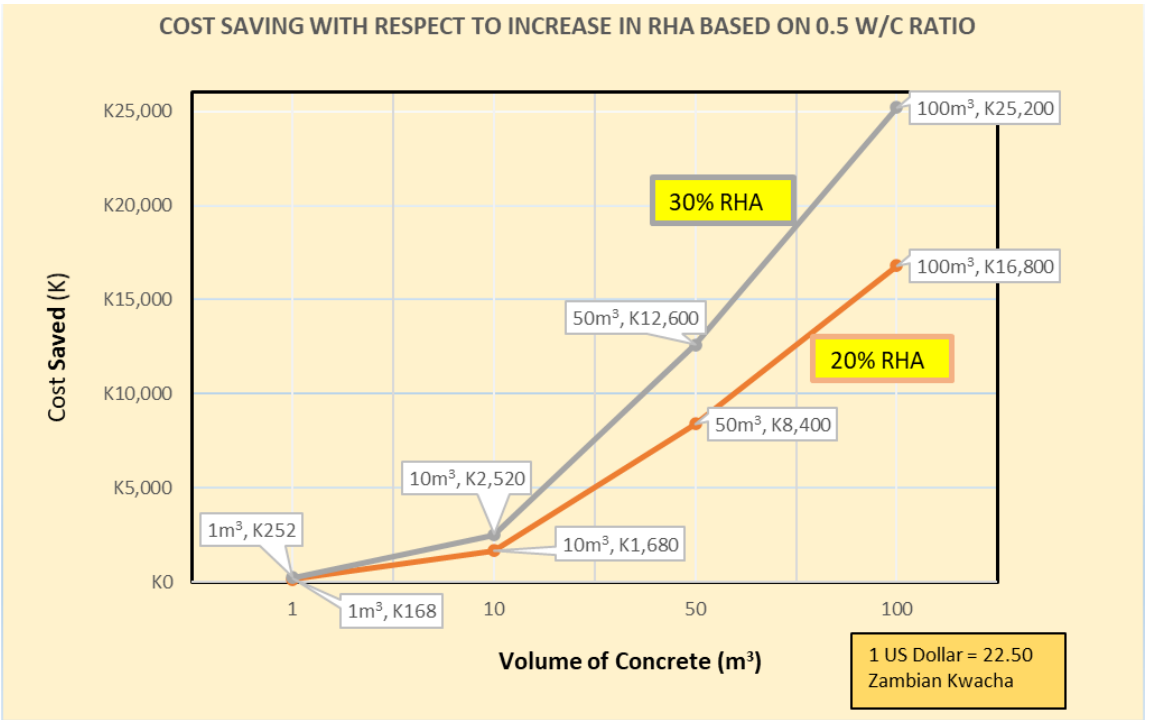

Fig. 11. Cost saving analysis for RHA-based concrete at a 0.5 water–cement ratio

RHA. Results indicate that the optimum cement replacement with RHA was at 20 %, and this is only applicable to the 0.5 water–cement ratio mix because it was more fluid and workable, as already explained under the slump and compressive strength subheadings. Fig. 10 shows that a saving of ZMW 1 680 (USD 74.6) can be made on 20 % RHA content for every 10 m^3 of 18 Mpa concrete made, while a saving of ZMW 2 520 (USD 112) saving can be made on 30 % RHA content for every 10 m^3 of 14 MPa concrete, which is suitable for light duty concrete uses. These amounts of savings are significant for Zambian rural residents, making this information highly valuable and beneficial to rural rice-growing communities. These savings would significantly contribute to improved livelihood as the money could be used on other development projects or poverty alleviation. All these savings are based on the 0.5 water–cement ratio, which is the cheaper concrete because it uses less cement content even before replacing some of the cement with RHA.

5. Value and benefits of the research to the industry

The research acknowledges the use of RHA as cement replacement, as seen in the literature review section. First, the study revealed that the local RHA in Zambia performs just like other RHAs in other countries and, therefore, can be used to partially replace cement in concrete, as seen from the results section of the paper. This is because the results are consistent with the literature review findings. Secondly and most importantly, the results from this research provide valuable information to rice growers in Zambian rural areas on how they can turn the rice husk waste to ash that can be used to improve the quality of their infrastructure. Many households in rural Zambia use clay floors and surface beds for house floors. The rice husk ash would help to reduce the cost of concrete, thereby making affordable concrete for the structures. A major contribution to livelihood improvement can be made by converting waste into a useful resource for making cheaper and affordable concrete. The rural Zambian rice-growing communities may not afford sophisticated furnaces to produce rice husk ash, but local kilns used for making clay burnt bricks may be used for that purpose. These results may be extended to other regions of the continent in promoting the use of RHA as a partial replacement of cement in the rural rice-growing regions. Although many scholars have widely studied this topic for decades, this is the first known paper offering a detailed cost–benefit analysis of the RHA use in concrete in the Zambian construction for the benefit of the rural rice-growing communities as a way of improving the quality of their physical infrastructure, including housing and other agricultural infrastructure support systems.

6. Limitations of the research

As an exploratory study, the research focussed on fully-cured concrete results at 28 days for analysis. Other experiments, such as cumulative compressive strength at seven, 14 and 21 days and beyond 28 days for normal concrete and RHA-based concrete, were not carried out because the primary properties of RHA-based concrete performance needed to be established in this exploratory research. Concrete results at 28 days were enough to make a conclusive analysis of this exploratory study. Besides, the study did not use a superplasticiser to overcome concrete fluidity and compressive strength challenges caused by the introduction of RHA. The next study, which will be full-scale, will introduce a superplasticiser along with cement tests and trail mixes to ensure that all parameters are established at the beginning of the study. It must be noted that there is no established data to confirm the performance of cement and plasticisers in Zambia, hence, the need to carry out detailed cement tests and multiple concrete mix trials.

Conclusions

The research revealed that many studies had been undertaken on partial replacement of cement with up to 30 % of RHA to produce good and functional concrete. Besides, the research established that it was feasible to utilise RHA as a way of turning it from waste to a resource. The study indicates that the optimal cement replacement by RHA was 20 % and 30 %, which resulted in concrete compressive strength of 18 Mpa and 14 MPa at 0.5 W/C ratio, respectively. This concrete grade can be used in foundation footings, medium-duty concrete surface beds, agricultural working bays etc. Unlike many other papers on the same subject, this paper presents cost–benefit analysis particularly aimed at improving livelihood for rural communities in rice-growing areas. The results

indicated that cost benefits were applicable to significant volumes of cheaper concrete production with savings of ZMW 1 680 (USD 74.6) for every 10 m^3 of 18 MPa concrete produced using a 20 % cement replacement with RHA. This translated into the cost reduction of concrete by 12.5 %, which is significant, particularly for higher volumes of concrete. Further, a saving of ZMW 2 520 (USD 112) for every 10 m^3 of 14 MPa concrete produced using a 30 % cement replacement with RHA. This research has provided useful data that can be used to make informed decisions by rice-growing communities in the use of RHA as concrete resource material. An education programme would need to be designed to train rice-growing communities to use RHA and partial cement material. Although the study objective was reached by confirming that RHA-based concrete is functional in low-income communities, one limitation of the study remains, i.e., the strength tests at 60 days and 90 days were not performed; therefore, future studies could consider making strength tests beyond 28 days in addition to introducing other elements, such as fly ash, copper tailings and other waste materials that may be recycled in an effort to reduce the depletion of natural resources while bringing down the cost of concrete. Further, the use of superplasticisers must be explored at many levels of concrete production, especially for cement and fine aggregate replacement-based concrete to improve fluidity and performance. This study has also demonstrated that cement testing and multiple trial mixes are important before proceeding with full-scale studies and industry application.

Acknowledgements

The publication of the article for 11th International Conference on Engineering, Project, and Production Management - EPPM2021 was financed in the framework of the contract no. DNK/SN/465770/2020 by the Ministry of Science and Higher Education within the "Excellent Science" programme.

Literature

Ahsan, M. B., & Hossain, Z. (2018). Supplemental use of rice husk ash (RHA) as a cementitious material in concrete industry. *Construction and Building Materials, 178,* 1-9. doi: 10.1016/j.conbuildmat.2018.05.101

Akeke, G. A., Ephraim, M. E., Akobo, I. Z. S., & Ukpata, J. O. (2013). Structural properties of rice husk ash concrete. *International Journal of Engineering*, *3*(3), 8269.

Alam, S. (2015). *Properties of brick aggregate concrete using rice husk ash (RHA) cement as binding material*. Master thesis. Dhaka, Bangladesh: Bangladesh University of Engineering & Technology.

Al-Khalaf, M. N., & Yousif, H. A. (1984). Use of rice husk ash in concrete. *International Journal of Cement Composites and Lightweight Concrete*, *6*(4), 241-248.

Allam, M., & Garas, G. (2010). Recycled chopped rice straw–cement bricks: an analytical and economical study. *WIT Transactions on Ecology and the Environment*, *140,* 79-86.

Białas, A. (2016). Cost-benefits aspects in risk management. *Polish Journal of Management Studies*, *14*(1), 28-39.

Bui, D. D. (2001). *Rice Husk Ash as a Mineral Admixture for High Performance Concrete*. PhD thesis. Delft, The Netherlands: University of Technology.

Calica Jr, M. G. (2008). Influence of rice husk ash as supplementary material in cement paste and concrete. *NLR Journal*, *2*, 80-92.

Chanda Kunda (2000). *Blending natural fine aggregate with recycled fine aggregate to produce concrete*. Thesis. Zambia: Copperbelt University.

Christy, C. F., & Tensing, D. (2010). Effect of Class-F fly ash as partial replacement with cement and fine aggregate in mortar. *Indian Journal of Engineering and Materials Sciences*, *17*, 140-144.

Creswell, J. W. (2009). *Research Design Qualitative, Quantitative and Mixed Methods Approaches*. 3rd ed. Los Angeles: SAGE Publications Inc.

Dandautiya, R., & Singh, A. P. (2019). Utilization potential of fly ash and copper tailings in concrete as partial replacement of cement along with life cycle assessment. *Waste Management*, *99*, 90-101.

Dhaka, J. K., & Roy, S. (2015). Utilization of fly ash and cow dung ash as partial replacement of cement in concrete. *International Journal of Civil & Structural Engineering*, *6*(1), 34-39.

Divsholi, B. S., Lim, T. Y. D., & Teng, S. (2014). Durability properties and microstructure of ground granulated blast furnace slag cement concrete. *International Journal of Concrete Structures and Materials*, *8*(2), 157-164.

Emmitt, S., & Gorse, C. A. (2014). *Advanced Construction of Buildings*. 3rd ed. John Wiley and Sons.

Ephraim, M. E., Akeke, G. A., & Ukpata, J. O. (2012). Compressive strength of concrete with rice husk ash as partial replacement of ordinary Portland cement. *Scholarly Journal of Engineering Research*, *1*(2), 32-36.

Fapohunda, C., Akinbile, B., & Shittu, A. (2017). Structure and properties of mortar and concrete with rice husk ash as partial replacement of ordinary Portland cement – A review. *International Journal of Sustainable Built Environment*, *6*(2), 675-692.

Hallingberg, B., Turley, R., Segrott, J., Wight, D., Craig, P., Moore, L., & Moore, G. (2018). Exploratory studies

to decide whether and how to proceed with full-scale evaluations of public health interventions: a systematic review of guidance. *Pilot and Feasibility Studies*, *4*(1), 1-12.

Jatoi, M. A., Solangi, G. S., Shaikh, F. A., & Rajput, S. (2019). Effect of Lakhra fly ash as partial replacement of cement in traditional concrete. *Mehran University Research Journal of Engineering & Technology*, *38*(4), 1045-1056.

Joel, M. (2010). A review of partial replacement of cement with some agro wastes. *Nigerian Journal of Technology*, *29*(2), 12-20.

Kanthe, V. N. (2021). Effect of Superplasticizer on Strength and Durability of Rice Husk Ash Concrete. *Iranian (Iranica) Journal of Energy & Environment*, *12*(3), 204-208.

Krishna, N. K., Sandeep, S., & Mini, K. M. (2016). Study on concrete with partial replacement of cement by rice husk ash. *IOP conference series: materials science and engineering*, *149*(1), 012109.

Krishna, R., Chaudhary, M., & Sen, A. (2015). Effect of partial replacement of cement by rice husk ash in concrete. *International Journal of Science and Research*, *4*(5), 1572-1574.

Kundu, S., Aggarwal, A., Mazumdar, S., & Dutt, K. B. (2016). Stabilization characteristics of copper mine tailings through its utilization as a partial substitute for cement in concrete: preliminary investigations. *Environmental Earth Sciences*, *75*(3), 227.

Le, H. T., & Ludwig, H. M. (2016). Effect of rice husk ash and other mineral admixtures on properties of self-compacting high-performance concrete. *Materials & Design*, *89*, 156-166.

Map of Zambia showing rice growing area and provinces as discussed under the background. Retrieved from https://www.pinterest.com/pin/7704674487257-82191

Mo, K. H., Alengaram, U. J., & Jumaat, M. Z. (2015). Utilization of ground granulated blast furnace slag as partial cement replacement in lightweight oil palm shell concrete. *Materials and Structures*, *48*(8), 2545-2556.

Muhit, I. B., Ahmed, S. S., Amin, M. M., & Raihan, M. T. (2013). Effects of silica fume and fly ash as partial replacement of cement on water permeability and strength of high-performance concrete. In *4th International Conference on Advances in Civil Engineering, AETACE, Association of Civil and Environmental Engineers*.

Muleya, F. (2000). *Quality management in Construction*. Thesis. Zambia: Copperbelt University.

Muleya, F., & Nwaubani, S. (2018). Sustainable Partial Cement and Water Replacement in Concrete Using PFA and Super Plasticiser. *Case Studies Journal, 5*(5), 34-40.

Muleya, F., Mulenga, B., Zulu, S. L., Nwaubani, S., Tembo, C. K., & Mushota, H. (2021). Investigating the suitability and cost-benefit of copper tailings as partial replacement of sand in concrete in Zambia: an exploratory study. *Journal of Engineering, Design and Technology*, *19*(4), 828-849. doi: 10.1108/JEDT-05-2020-0186

Muthadhi, A. A., & Kothandaraman, R. (2007). Rice husk ash – Properties and its uses: a review. *Journal of The Institution of Engineers (India)*, *88*, 50-56.

Muthandhi, A., & Kothandaraman, S. (2010). Optimum production conditions for reactive rice husk ash. *Materials and Structures*, *43*(9), 1303-1315.

Naik, T. R. (2008). Sustainability of concrete construction. *Practice Periodical on Structural Design and Construction*, *13*(2), 98-103.

Novikov, A. M., & Novikov, D. A. (2019). *Research methodology: From philosophy of science to research design*. CRC Press.

Obilade, I. O. (2014). Use of rice husk ash as partial replacement for cement in concrete. *International Journal of Engineering*, *5*(04), 8269.

Olafusi, O. S., & Olutoge, F. A. (2012). Strength properties of corn cob ash concrete. *Journal of Emerging Trends in Engineering and Applied Sciences*, *3*(2), 297-301.

Oyekan, G. L., & Kamiyo, O. M. (2011). A study on the engineering properties of sandcrete blocks produced with rice husk ash blended cement. *Journal of Engineering and Technology Research*, *3*(3), 88-98.

Özbay, E., Erdemir, M., & Durmuş, H. İ. (2016). Utilization and efficiency of ground granulated blast furnace slag on concrete properties–A review. *Construction and Building Materials*, *105*, 423-434.

Pal, S. C., Mukherjee, A., & Pathak, S. R. (2003). Investigation of hydraulic activity of ground granulated blast furnace slag in concrete. *Cement and Concrete Research*, *33*(9), 1481-1486.

Pode, R. (2016). Potential applications of rice husk ash waste from rice husk biomass power plant. *Renewable and Sustainable Energy Reviews*, *53*, 1468-1485.

Podolyakina, N. (2016). Product reliability and warranty period as a cost-forming factors. *Business: Theory and Practice*, *17*(4), 361-369. doi: 10.3846/btp.17.11131

Rafieizonooz, M., Mirza, J., Salim, M. R., Hussin, M. W., & Khankhaje, E. (2016). Investigation of coal bottom ash and fly ash in concrete as replacement for sand and cement. *Construction and Building Materials*, *116*, 15-24.

Rajagopalan, G. (2019). Durability of alumina silicate concrete based on slag/fly ash blends against corrosion. *Engineering, Construction and Architectural Management*, *26*(8), 1641-1651. doi: 10.1108/ECAM-08-2018-0345

Rajamane, N. P., Peter, J. A., & Ambily, P. S. (2007). Prediction of compressive strength of concrete with fly ash as sand replacement material. *Cement and Concrete Composites*, *29*(3), 218-223.

Ramezanianpour, A. A., Mahdikhani, M., & Ahmadibeni, G. H. (2009). The effect of rice husk ash on mechanical properties and durability of sustainable concretes. *International Journal of Civil Engineering, 7*(2), 83-91.

Reshma, T. V., Manjunatha, M., Sankalpasri, S., & Tanu, H. M. (2021). Effect of waste foundry sand and fly ash on mechanical and fresh properties of concrete. *Materials Today: Proceedings*. doi: 10.1016/j.matpr.2020.12.821

Salvador, R. P., Rambo, D. A., Bueno, R. M., Silva, K. T., & de Figueiredo, A. D. (2019). On the use of blast-

furnace slag in sprayed concrete applications. *Construction and Building Materials*, *218*, 543-555.

Sharma, R. K. (2014). Effect of substitution of cement with rice husk ash on compressive strength of concrete using plastic fibres and super plasticizer. *KSCE journal of civil engineering*, *18*(7), 2138-2142.

Shukla, A., Singh, C. K., & Sharma, A. K. (2011). Study of the properties of concrete by partial replacement of ordinary Portland cement by rice husk ash. *International Journal of Earth Sciences and Engineering*, *4*(6), 965-968.

Siddika, A., Al Mamun, M. A., Alyousef, R., & Mohammadhosseini, H. (2020). State-of-the-art-review on rice husk ash: A supplementary cementitious material in concrete. *Journal of King Saud University-Engineering Sciences*, *33*(5), 294-307. doi: 10.1016/j.jksues.2020.10.006

Singh, A. (2008). *Cost benefit analysis of green buildings*. New Delhi: Department of building Engineering & Management.

Singh, B. (2018). Indian Institute of Technology Roorkee, Roorkee, India. *Waste and Supplementary Cementitious Materials in Concrete: Characterisation, Properties and Applications*, 417-460. doi: 10.1016/B978-0-08-102156-9.00013-4

SNRDS (2016). Second National Rice Development Strategy 2016-2020. Retrieved from https://www.riceforafrica.net/images/countries/NRDS_rev/NRDS2_Zambia_en.pdf

Swetha, K., Bhavya, S., & Anadinni, S. (2015). Characterization of materials by partially replacing cement by copper ore tailing and sand by iron ore tailing. *International Journal of Research in Engineering and Technology*, *4*(7), 374-377.

Thiedeitz, M., Schmidt, W., Härder, M., & Kränkel, T. (2020). Performance of rice husk ash as supplementary cementitious material after production in the field and in the lab. *Materials*, *13*(19), 4319.

Van Lam, T., Bulgakov, B., Bazhenov, Y., Aleksandrova, O., & Anh, P. N. (2018, June). Effect of rice husk ash on hydrotechnical concrete behavior. In *IOP Conference Series: Materials Science and Engineering*, *365*(3), 032007.

Zambia's rice production from 1978 to 2019. Retrieved from https://knoema.com/atlas/Zambia/topics/Agriculture/Crops-Production-Quantity-tonnes/Rice-paddy-production

Zareei, S. A., Ameri, F., Dorostkar, F., & Ahmadi, M. (2017). Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties. *Case Studies in Construction Materials*, *7*, 73-81.

Volume 13 • Issue 2 • 2021

sciendo

ISMSME International Society for Manufacturing, Service and Management Engineering

received: 1 April 2021
accepted: 15 August 2021

pages: 142-150

Factors influencing the adoption of Building Information Modelling (BIM) in the South African Construction and Built Environment (CBE) from a quantity surveying perspective

Berco Venter Sams Pfukani Ngobeni
Hendri du Plessis

ABSTRACT
The construction industry has often been described as stagnant and out-of-date due to the lack of innovation and innovative work methods to improve the industry (WEF, 2016; Ostravik, 2015). The adoption of Building Information Modelling (BIM) within the construction industry has been relatively slow (Cao et al., 2017), particularly in the South African Construction and Built Environment (CBE) (Allen, Smallwood & Emuze, 2012). The purpose of this study was to determine the critical factors influencing the adoption of BIM in the South African CBE, specifically from a quantity surveyor's perspective, including the practical implications. The study used a qualitative research approach grounded in a theoretical framework. A survey questionnaire was applied to correlate the interpretation of the theory with the data collected (Naoum, 2007). The study was limited to professionals within the South African CBE. The study highlighted that the slow adoption of BIM within the South African CBE was mainly due to a lack of incentives and subsequent lack of investment towards the BIM adoption. The study concluded that the South African CBE operated mainly in silos without centralised coordination. The BIM adoption was only organic. Project teams were mostly project orientated, seeking immediate solutions, and adopted the most appropriate technologies for the team's composition. The study implies that the South African CBE, particularly the Quantity Surveying profession, still depends heavily on other role-players in producing information-rich 3D models. Without a centralised effort, the South African Quantity Surveying professionals will continue to adopt BIM technology linearly to the demand-risk ratio as BIM maturity is realised in the South African CBE.

KEY WORDS
Building Information Modelling (BIM), South African Construction and Built Environment (CBE), design silos

10.2478/emj-2021-0027

Hendri du Plessis

University of the Free State, South Africa
ORCID 0000-0002-6342-0702

Corresponding author:
e-mail: duplessishb@ufs.ac.za

Berco Venter

University of the Free State, South Africa

Sams Pfukani Ngobeni

University of the Free State, South Africa

Introduction

The construction industry is one of the biggest industries globally, with one of the most significant numbers of employees. The opposite is true about the industry when it comes to being innovative. The construction industry has often been described as stagnant and out of date due to the lack of innovative work methods to improve the industry. Although some new technologies have emerged in the industry's market, innovation and adoption of innovation

Venter, B., Ngobeni, S. P., & du Plessis, H. (2021). Factors influencing the adoption of Building Information Modelling (BIM) in the South African Construction and Built Environment (CBE) from a quantity surveying perspective. *Engineering Management in Production and Services, 13*(3), 142-150. doi: 10.2478/emj-2021-0027

in the sector are still low (WEF, 2018; Abubakar et al., 2014). This includes Building Information Modelling (BIM), Integrated Project Delivery (IPD), Integrated Design Processes (IDP) and Lean construction.

The adoption of Building Information Modelling (BIM) within the Construction Industry has been relatively slow (Cao et al., 2017), particularly in the South African Construction and Build Environment (CBE) (Allen, Smallwood & Emuze, 2012).

BIM can be defined as a set of interacting tools, processes, and technologies guided by norms and rules to support practitioners in the construction environment developing a building project (Eastman et al., 2011; Al Safarini et al., 2021). BIM can be extremely beneficial to construction companies willing to devote the time and finances required to adopt BIM fully. It is meant to ease the collaboration process between the different stakeholders. BIM is the collaboration tool that makes it possible to bring all different construction disciplines together into one single authoritative project model. It is also beneficial to the Quantity Surveyor as a valuable measurement and quantification tool that makes the project more transparent and enhances project efficiency (ASAQS, 2017).

Even though BIM has the potential to benefit the South African CBE and, particularly, the Quantity Surveyor, numerous factors still affect the adoption of BIM in South Africa by QS firms. Therefore, its adoption is still very slow (Allen, Smallwood & Emuze, 2012). The purpose of this study was to determine the critical factors influencing the adoption of BIM in the South African CBE from a Quantity Surveyor's perspective. This research endeavoured to highlight the aspects that can be addressed or focussed on by BIM users in the industry. The study's objective was to determine the present level of awareness, industry readiness, the current rate of use and the perception of Quantity Surveyors regarding the adoption of BIM in the CBE.

The study aimed to establish the current and most pressing challenges causing the South African CBE's seemingly slow adoption of BIM from a Quantity Surveyor's perspective. This was accomplished by measuring the health of the industry against the BIM maturity model (Sacks et al., 2018) and by comparing two data collection sets. One endeavoured to establish the common challenges towards BIM adoption, while the second investigated the relationship between company size and BIM adoption.

The study mainly focused on the South African CBE from a Quantity Surveyor's perspective.

1. Literature review

1.1. Quantity Surveyor

The Quantity Surveyor (QS) is seen as the financial and development consultant that provides advice to either clients or contractors on contractual arrangements and cost advice. The QS is allowed to prepare contractual documentation for the project and also perform cost planning and cost management throughout the project to ensure that the development stays within the budget. According to the Quantity Surveyors' Act of 2000, anyone who wants to become a qualified QS in South Africa needs the necessary qualifications and experience and need to register with the South African Council of Quantity Surveyors (SACQSP) before being allowed to provide services to the public (Maritz & Siglé, 2016).

According to the Royal Institute for Charted Surveyors (RICS, 2007), some of the traditional QS functions include:

- Preparing the budget by determining the client's requirements and using estimates.
- Preparing feasibility studies of the proposed project.
- Preparing the Bills of Quantities used to obtain the best possible tenders from numerous possible contractors.
- Preparing contractual documentation.
- Monitoring costs while providing reports to clients throughout the project.
- Determining the Final Account of the project.

Larsen (in Ostravik, 2015) concludes that technology adoption diffuses firms and individuals, mainly from project to project. His Innovation Diffusional Network highlights two main parameters: broader institutional forces and peer pressure. These parameters further incorporate industry parameters, namely, negotiation space, contextual thresholds, group thinking, power available, selective exposure, actor thresholds, and the notion of needs. These parameters aptly explain how the BIM adoption is currently taking place. This complex, innovative diffusion can further be divided into two levels: diffusion among firms and diffusion among individuals within a firm.

The functions that a QS provides to the client or contractor are extremely time-consuming and might contain errors due to incorrect quantity take-offs for projects with large numbers of drawings (Mayouf, Gerges & Cox, 2019). When variations or changes

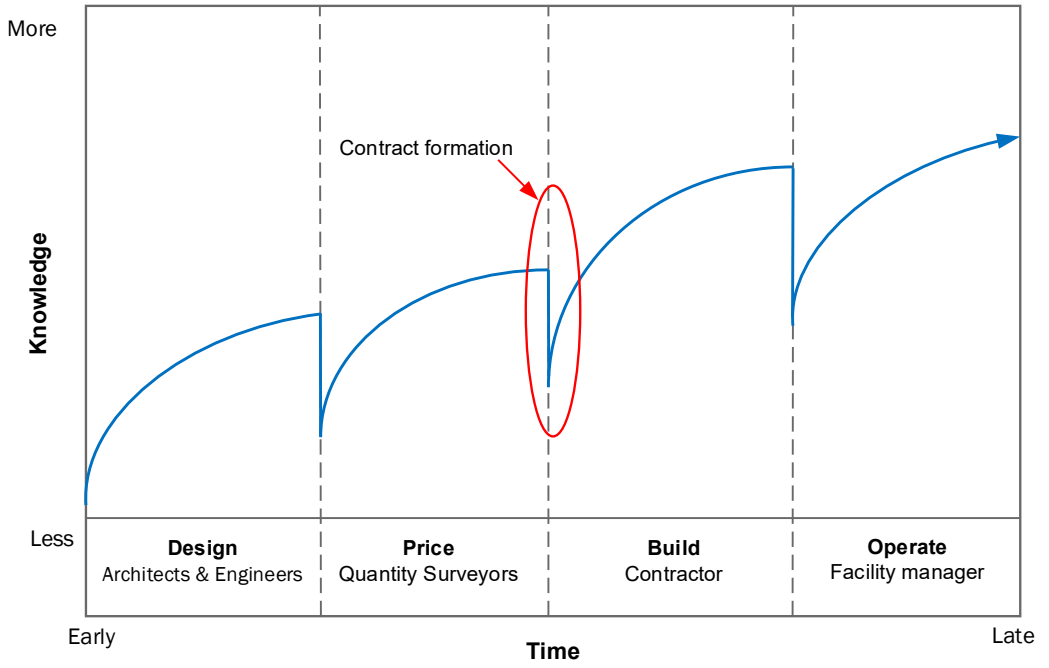

Fig. 1. Traditional method of information flow from one process to the other
Source: (Bernstein, 2015, video, cited du Plessis, 2019. p. 125).

occur in the traditional "manual" processes, it is time-consuming to correct and often leads to inaccurate estimates (RICS, 2013). It is essential to note that the quality of the drawings will also have a major impact on the accuracy of the estimates (Sacks et al., 2018; Exactal, 2018). Inaccurate drawings are among the biggest challenges faced by the QS. Subsequently, this highlights the importance of the QS to be a part of the design stage as early as possible, to collaborate with the designers and minimise errors. The understanding of the scope and the feedback to other consultants are crucial for proper Integrated Project Management of a construction project (Du Plessis & Oosthuizen, 2018).

To summarise, the design consultants continually produce more information, which the QS has to interpret to compile the procurement documents. This summary is depicted in Fig. 1.

Fig. 1 clearly shows that information is continually lost as it is passed to the next role player. This emphasises the benefit of BIM, which is further discussed in the next section.

1.2. Building Information Modelling (BIM)

Allen, Smallwood and Emuze (2012) claim that by offering a platform that makes it easier to handle, identify and avoid conflicts in project designs, BIM offers potential benefits to architects during the design phase of a construction project. They further claim that projects would benefit from this system as the cost of rework due to design flaws and disputes will be drastically lower or non-existent. Uysal (in Kocakaya, Namli & Isikdag, 2019) claims that the on-site use of BIM in construction projects offers visual and appropriate information to contractors, which is obtained on-site at a reasonable time. Consequently, there is a likelihood of reducing the number of requests for information (RFI), disputes, and conflicts frequently found on construction sites.

The construction industry has fallen victim numerous times to being labelled as inefficient with low productivity levels. Due to this recurring problem, an effort has been made to provide new techniques and technologies to improve the productivity levels, enhance the quality of work and reduce the overall construction costs throughout the project. An innovative technology that is believed to be a step in the right direction for the construction industry is BIM (Panuwatwanich, 2013).

The BIM maturity levels currently range from level 0 to 3 (four levels). BIM maturity levels are defined according to criteria with which BIM users are required to comply (to be BIM-compliant). At levels 0 and 1, there is a lack of BIM use, or other systems are being overused (Sacks et al., 2018). In April 2016, the UK Government mandated that any public sector's construction project had to comply with BIM level 2. Level 2 requires structured data for a built asset that provides collaboration throughout

the supply chain. Level 3 will be targeted once the entire construction industry has managed to comply with level 2 (Malleson, 2018).

Integrating the cost element into BIM creates the fifth dimension (5D) (4D BIM refers to scheduling and 6D refers to facilities management). This is seen as a step in the right direction to improve cost management by many competitive firms (Smith, 2016). According to Smith (2016), BIM allows the Quantity Surveyor more time to provide cost advice and cost knowledge to the project team because the time to produce estimates, quantity take-offs, bills of quantities and other time-consuming data is greatly reduced. 5D BIM enables the QS to perform functions, such as quantity take-offs, measuring directly from a 5D BIM model that is linked to estimating software that automatically updates when changes occur (Haque & Mishra, 2007).

The United Kingdom (UK), Ireland and New Zealand are examples of governments taking a leading role in the BIM implementation. Since April 2016, the UK has implemented a mandate that requires all projects funded by the central government to be on the BIM maturity level 2. The National BIM Report (Waterhouse, 2019) states that BIM awareness and adoption levels had increased from 10 % in 2011 to 70 % in 2019. In Ireland, the National BIM Report state that, from the 116 respondents in their research, 76 % have adopted BIM in their work environment. According to the BIM Acceleration Committee (Waterhouse, 2019), New Zealand has experienced a total growth rate of only 4 % in four years as it grew from 55 % in 2016 to 59 % in 2019. Although these countries are deemed as countries leading in the BIM adoption, there are still numerous barriers influencing the adoption of BIM in the UK and Ireland.

The South African CBE are years behind other countries with multiple and largely fragmented industries. Many QS companies are small, two to three-man practices, with diverse spectra of clients and types of projects. Clients also vary by financial strengths and the type of projects. This leads to different technological requirements and project team compositions. The South Africa CBE should show improvement in the entire value chain of the Project Life Cycle (PLC) in an effort to create a market for those producing usable data (Potgieter, 2017). The BIM Institute, in conjunction with the ASAQS, have taken the initiative to compile an Elemental Classification System to assist model developers in producing such information for the Quantity Surveyor, who, in turn, can convey it to the contractors. The objective is to standardise the way BIM information is classified within the model (ASAQS, 2018). This correlates with the suggestion of better collaboration between the supply chain and stakeholders (Odubiyi et al., 2019). Waiting for the South African Government will not promote the BIM implementation (Potgieter, 2017), and the BIM adoption will be driven by other stakeholders in an organic manner.

As a result of the COVID-19 pandemic, the South African CBE has experienced an additional economic decline over and above the one of 2016 (South Africa, 2021). This, together with the factors mentioned above, led to the provisional conclusion that the South African CBE is currently adopting BIM in an organic manner to address each project's demands in a way most suitable for compiling the project team with each organisation meeting the minimum requirements on an ad hoc basis.

2. Research methods

Two research data sets were used in an endeavour to answer the main research question. Two separate data sampling questionnaires were used to enable exploration and placement of the current state of the South African CBE in relation to the BIM maturity model.

A qualitative method was used on this project, placing the interpretation of theory on the data collected. A survey approach was used for data gathering purposes (Naoum, 2007), with a total of 61 professionals participating in the survey.

The two surveys were divided into the following data collection themes:

1. Factors influencing the adoption of BIM in the South African CBE.
2. The connection between organisational size and the adoption of BIM in the South African CBE.

For this study, a non-probability sampling design was used to determine the sample. This sampling process does not provide an equal chance for respondents to be selected within the population as it makes use of subjective methods to select which respondents or individuals will be forming part of the sample (Trobia, 2008). The sampling method of this study was convenience sampling. Convenience sampling is a sampling technique of non-probability sampling where respondents are selected based on the convenience of their nearness and accessibility to the researcher (Leedy & Ormond, 2010).

Tab.1. Background of respondent firms and BIM implementation

Location of work		Value of work		BIM usage		Organisational size	
Local and international projects	41%	Below R20mil	32%	Full use	0%	Micro: 0-10	13
International projects only	6%	R20mil to R100mil	32%	Partial use	47%	Small: 11-50	9
Local projects only	53%	Above R 100mil	35%	Not at all	53%	Medium: 51-250	9
						Large: 250 and above	3

Tab. 2. Identification of barriers in the South African CBE adoption of BIM

	Strongly disagree (1)	Somewhat disagree (2)	Somewhat agree (3)	Agree (4)	Strongly agree (5)	Mean
Is there a lack of incentive to adopt in the South African CBE	0%	0%	15%	29%	56%	10.0
Is there a lack of client demand	0%	3%	15%	50%	32%	9.3
Is BIM worth it	2%	3%	18%	62%	15%	8.7
Will BIM improve the accuracy of estimates	0%	9%	21%	46%	24%	8.7
Will BIM improve communication between stakeholders	6%	3%	29%	44%	18%	8.3
Will BIM enhance the efficiency of the construction process and reducing construction costs?	12%	6%	26%	47%	9%	7.6
Is BIM understandable	6%	12%	47%	32%	3%	7.1
Is the current 2D software good enough	9%	24%	35%	29%	3%	6.6

The study incorporated primary data collected through the process explained above, together with the secondary data (Naoum, 2007) collected by reviewing the literature to reach a conclusion. The research furthermore went through an ethical clearance process at the University of the Free State.

3. Research results

3.1. Factors influencing the adoption of BIM in the South African CBE

The first study used a qualitative questionnaire that was distributed among Quantity Surveying firms in South Africa. The objective was to establish a baseline for the barriers to adopting BIM by Quantity Surveyors and the possible link between the organisation and/or project size. Table 1 illustrates the background of these firms on location, value, BIM implementation, and the size of their organisation.

A relationship may be observed between the monitory value of projects and the adoption of BIM. It does, however, indicate that none of the firms that responded had fully adopted BIM. Thus, without a centralised effort, BIM is being adopted systematically through the BIM maturity levels. A clearer dataset would be required to evaluate the current state of BIM maturity in the South African CBE. Table 2 illustrates the respondents' perceptions of BIM barriers in the South African CBE, ranked according to the barriers (the relevant factors shown in the appropriate headings).

Table 2 indicates that most respondents are eagerly waiting for BIM collaboration and are exploring the possible benefits of BIM adoption. Most respondents see the use of BIM-compatible software as a means to improve the accuracy and efficiency of measurement work; however, they are currently using what is required to get the job done.

Because the first study provided limited answers on BIM adoption and maturity levels of the South African CBE and, in particular, from a QS perspective, the subsequent study attempted to address this shortfall.

3.2. Connection between organisational size and the adoption of BIM in the South African CBE

The study sought to find clarity from the greater South African CBE and wanted to establish a connection between the size of the organisation and the adoption of BIM. Again, a qualitative questionnaire was used to gather data from Project Managers,

Architects, Quantity Surveyors, Engineers and Contractors.

Table 3 illustrates the findings of the data collection process, in which the respondents had to indicate their agreement, neutrality or disagreement with the statements. The means of the questionnaire were subsequently calculated, as shown in Table 3.

A standard t-test was done against the standard deviation of the different organisation sizes and the barriers to establish the relevance of the data. The t-test revealed that a significant trend occurred between large organisations and other organisation sizes. However, a very low significance was observed between the micro- to medium-sized organisations (Table 4).

Tab. 3. BIM adoption barriers compared to organisational size (D=Disagree; N=Neutral; A=agree)

BIM adoption barriers						
Disagree (1); neutral (2); agree (3)			Organisation size			
			Micro: 0-10	Small: 11-50	Medium: 51-250	Large: 250 & above
Barriers	1	Cost of additional resources	2.4	2.9	2.6	1.7
	2	Increased level of risk and liability	2.6	2.4	1.7	1.4
	3	Current policies for procurement methods and procedures	2.6	2.8	1.9	2.0
	4	Lack of comprehensive frame or implementation plan	2.4	3.0	2.4	1.7
	5	Lack of skills and training	2.6	3.0	2.9	1.6
	6	Organizational structure and culture challenges (lack of organization support)	2.8	2.1	2.6	2.1
	7	Lack of demand by clients	2.6	2.6	2.6	2.0
	8	Lack of BIM awareness	2.6	2.6	2.6	2.0

Tab. 4. T-test between barriers and different organisation data sets

	a) Micro against other		b) Small against other		c) Medium against other		d) Large against other	
P-values	a) & b)	0.43	b) & a)	0.43	c) & a)	0.31	d) & a)	0.00001
	a) & c)	0.31	b) & c)	0.17	c) & b)	0.17	d) & b)	0.00004
	a) & d)	0.00001	c) & d)	0.00004	c) & d)	0.004	d) & c)	0.004
Legend		Non-significant			Strongly significant			

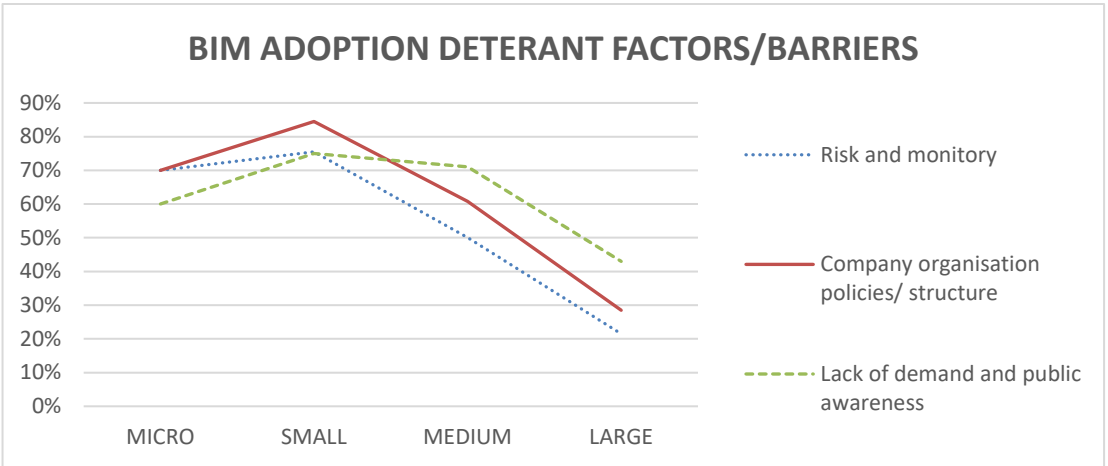

Fig. 2. Grouped barriers to BIM adoption [%]

The data is further grouped into three basic categories to enhance the placement theory discussion. The grouping allowed for a graphical representation of the percentage of the respondents that agreed with the statements, according to their organisational size:

From the second data set, a clearer perspective is provided on the organisations' size and uptake and/or positioning towards the BIM implementation. Fig. 2 shows a clear tendency for the larger firms to adopt BIM differently and different perceptions towards the barriers than smaller firms. An average of 70 % of micro firms and 76 % of small firms indicated that cost and risk are barriers for their company. In comparison, 70 % of medium-sized firms indicated that cost is a challenge, and only 29 % noted that it carried significant risk. Micro to medium-sized firms said that client demand and BIM awareness (60 % to 71 % agreement) were barriers to overcome, while only 43 % of large firms agreed with this statement.

4. Discussion of the results

The summarised criteria of barriers (risk and monetary; company organisational structure/policies and lack of demand) indicate that the larger firms experienced these barriers to BIM adoption differently than micro to medium-sized companies. Larger firms may be exposed to larger clients and/or more technical projects, putting them in a better position to invest in these technologies. These firms also conduct more international work, which may explain this perception. Smaller firms have different objectives than larger firms with different business models.

The conclusion from the above information is that the larger firms are more exposed to BIM because of a greater client/peer demand and, subsequently, the company's policies and associated risk towards monetary expenses. However, the micro and small firm comparison of risk/financial barriers is interesting. This might be explained by micro-enterprises considering BIM adoption more viable than small firms because of saving overhead costs. For these firms, the cost of appointing additional staff to grow the business might be offset by the cost/risk of empowering existing staff, acquiring BIM technology, and adopting these skills and services for clients.

Many large companies have different in-house services that promote greater collaboration between the project team members, leading to greater problem-solving abilities on projects. This, in turn, promotes a fundamentally different outlook towards BIM adoption.

Conclusions

The information from the literature, namely, that the majority of QS firms are micro-organisations, confirms the first data set's conclusion that QS firms are investigating BIM adoption; however, they are not compelled to do so because of demand. QS firms realise the potential of what BIM might provide in more efficient 5D BIM take-offs (measurements). However, facility managers and contractors depend on other consultants to provide the necessary information.

The literature indicated that BIM adoption follows the maturity levels. The South African CBE is no exception, showing similar trends to other countries. However, in South Africa, it is primarily driven by the private construction industry and not the Government. The subsequent result is that BIM is adopted by means of supply and demand or organically. The South African CBE maturity can currently be rated as BIM level 1, with the QS not benefiting from current models produced.

The research data also indicates that technology diffusion is currently taking place, with larger, more resourced companies taking the lead. However, the data shows that as 3D model production becomes more proficient throughout the differently sized organisations, the 4D to 6D producers will also become convergent.

With associations and councils working on solutions by producing quality standards through collaboration and learning from other countries, the South African CBE industry will gradually progress in BIM adoption. This, however, takes time, and without a more centralised drive by the Government, the adoption of BIM will still take place organically.

By addressing current challenges professionally, the industry is addressing future challenges by focusing on improving efficiency. Further research is required into a possible improvement of collaboration in the industry. Subsequently, the following suggestions are made from the study:

- The project team requires greater collaboration by focusing on the information needs of the dependent parties. The Elemental Classification System developed by the ASAQS in conjunction

with the BIM Institute and the South African Institute of Architecture (SAIA) is a great start.
- Implement BIM into the curriculum of educational facilities and provide in-house training to increase the knowledge and skills of current professionals.
- Clients should be educated to gain more knowledge with regards to how BIM can benefit them.
- The Government should follow in the footsteps of BIM-leading countries by implementing BIM mandates and standards that require companies to meet certain BIM criteria for them to take part in government projects.

Acknowledgements

The publication of the article for 11th International Conference on Engineering, Project, and Production Management - EPPM2021 was financed in the framework of the contract no. DNK/SN/465770/2020 by the Ministry of Science and Higher Education within the "Excellent Science" programme.

Literature

Abubakar, M., Ibrahim, Y. M., Kado, D., & Bala, K. (2014). Contractors Perception of the Factors Affecting Building Information Modelling (BIM) Adoption in the Nigerian Construction Industry. *Computing in Civil and Building Engineering*, 167-178.

Al Safarini, N., Hasan, A., Sakhrieh, A., Alnahhal, M., & Al Hazza, M. (2021). *Crucial Role of Efficient Communication on Construction Projects Progress, Deliverablesand Conflicts Reduction in the United Arab Emirates. Polish Journal of Management Studies*, *23*(1), 9-22.

Allen, C., Smallwood, J., & Emuze, F. (2012). *Building Information Modelling: South African architect's and contractor's perceptions and practices*. South Africa: Nelson Mandela Metropolitan University.

ASAQS – The South African Association of Quantity Surveying (2018). Announcing the ASAQS Elemental Class system. Retrieved from https://www.asaqs.co.za/news/395452/Announcing-the-ASAQS-Elemental-Class-system.htm

Bernstein, P. (2015). *TEDx Talks. The Future of Making Buildings*. Retrieved from https://www.youtube.com/watch?v=Kg0gbG1DAkk

Cao, D., Li, H., Wang, G., & Huang, T. (2017). Identifying and contextualising the motivations for BIM implementation in construction projects: An empirical study in China. *International Journal of Project Management*, *35*(4), 658-669.

Du Plessis, H. B. (2019). Facilitation of construction project management through building contracts: A South African perspective on the locally developed suites of contracts. *Acta Structilia*, *26*(1), 120147. doi: 10.18820/24150487/as26i1.5

Du Plessis, H. B., & Oosthuizen, P. M. (2018). Construction project management through building contracts, a South African perspective. *Acta Structilia*, *25*(1), 152181. doi: 10.18820/24150487/as25i1.6

Eastman, Ch., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook, a guide to building information modelling for owners, designers, engineers, contractors, and facility Managers*. 2nd ed. John Wiley & Sons.

Exactal (2018). Digital Drawing File Optimisation. For Measurement & Estimating Purposes Simple tips for a collaborative approach to improved drawing file intelligence. CostX6.7 Exactal Technologies Pty Ltd.

Haque, M. E., & Mishra, R. (2007). 5D virtual construction: Designer/constructors perspective'. In 10th International Conference on Computer and Information Technology, 1-4.

Kocakaya, M. N., Namli, E., & Isikdag, U. (2019). Building Information Management (BIM). A new approach to Project Management. *Journal of Sustainable Construction Materials and Technologies*, *4*(1), 323-332.

Leedy, P. D., & Ormond, J. E. (2010). *Practical research, planning and design*. 11th ed. Malaysia: Pearson Education Limited.

Malleson, A. (2018). The National BIM Report 2018. National Building Specification (NBS). RIBA Enterprises Ltd. Retrieved from https://www.thenbs.com/knowledge/the-national-bim-report-2018

Maritz, M. J., & Siglé, H. M. (2016). *Quantity surveying in South Africa*. Pretoria: Construction Economics Associates (Pty) Ltd.

Mayouf, M., Gerges, M., & Cox, S. (2019). 5D BIM: an investigation into the integration of quantity surveyors within the BIM process. *Journal of Engineering Design and Technology*, *17*(3), 537-553.

Naoum, S. G. (2007). *Dissertation Research & Writing for Construction Students*. 2nd ed. Elsevier Ltd.

Odubiyi, T. B., Aigbavboa1, C., Thwala, W., & Netshidane N. (2019). Strategies for building information modelling adoption in the South African construction industry. Conference. Modular and Offsite Construction (May 21 -24). Banff Springs, Canada.

Ostravik, F. (2015). Incentives for innovation in construction. In F. Ostravik, A. Dainty C. & Abbott (Eds.), *Construction Innovation* (pp. 13-28). United Kingdom: Wiley Balckwell.

Panuwatwanich, K., Wong, M. L., Stewart, R. A., & Mccarthy, T. J. (2013). Integrating building information modelling (BIM) into engineering education: an exploratory study of industry perceptions using social network data Publication Details. Retrieved from http://ro.uow.edu.au/eispapers/1920

Potgieter, P. (2017). The conflicted state of BIM in South Africa. Retrieved from http://www.ee.co.za/article/conflicted-state-bim-south-africa.html

RICS – Royal Institute of Chartered Surveyors (2007). Quantity surveyor services. Royal Institute of Char-

tered Surveyors. Retrieved from https://www.rics.org/globalassets/rics-website/media/upholding-professional-standards/sector-standards/construction/quantity-surveyor-services-rics.pdf

RICS – Royal Institute of Chartered Surveyors (2013). *Design and specification. RICS Professional Guidance, UK*. London, UK: RICS.

Sacks, R., Eastman C., Lee G., & Teicholz, P. (2018). *BIM handbook, a guide to building information modeling for owners, designers, engineers, contractors, and facility Managers*. 3rd ed. Hoboken, NJ: Wiley.

Smith, P. (2016). Project Cost Management with 5D BIM. *Procedia – Social and Behavioural Sciences*, *226*, 193-200.

South Africa (2021). Statistics South Africa. Statistical Release P0441, Gross domestic product. 8 June 2021. Retrieved from http://www.statssa.gov.za/publications/P0441/P04411stQuarter2021.pdf

The Association of South African Quantity Surveyors (2017). The conflicted state of BIM in South Africa. Retrieved from https://www.asaqs.co.za/news/348631/The-conflicted-state-of-BIM-in-South-Africa.htm?page=SalarySurveyReport

Trobia, A. (2008). Nonprobability sampling. In P. J. Lavrakas (Ed.), *Encyclopedia of survey research methods* (pp. 784-785). Thousand Oaks, CA: Sage Publications, Inc.

Waterhouse, R. (2019). The National BIM Report 2019. National Building Specification (NBS). RIBA Enterprises Ltd. Retrieved from https://www.thenbs.com/knowledge/national-bim-report-2019

WEF – World Economic Forum (2018). The Fourth Industrial Revolution is about to hit the construction industry. Here's how it can thrive. Retrieved from https://www.weforum.org/agenda/2018/06/construction-industry-future-scenarios-labour-technology/