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Exploring the need for a new paradigm in engineering management and the decision-making process in technology-based organisations

Simon P. Philbin   Donald Kennedy

ABSTRACT
Engineering management and engineering projects are subject to greater levels of uncertainty and complexity as part of the current dynamic and competitive industrial environment. Engineering managers need to navigate the arising challenges and consequently gain access to effective decision-making processes. Engineering education has a clear role to play here. However, formal education in quantitative methods is only part of the solution — engineers and engineering managers should also have access to a broader set of skills and knowledge to be effective in the industrial landscape. Therefore, we now need a new paradigm for engineering management and the decision-making process. This article draws on supporting material from the literature and the insights gained from a series of industrial cases using the participatory action research method and a process of inductive reasoning to allow synthesis of generalised propositions that are linked to the industrial cases and antecedent factors from the literature. The findings lead to a set of areas that require further development to support engineering managers to be more effective when dealing with increasing levels of uncertainty and complexity. This includes a number of areas, which are as follow: the need for engineering managers to have enhanced professional skills and knowledge; the importance of experience-based judgement; effective knowledge management; supportive leadership and overall organisational culture; and a holistic approach to decision-making. The research study has practical relevance to engineering management practitioners working in industrial companies to support self-evaluation and professional development. The findings are also pertinent to academic researchers seeking to evaluate decision-making models as part of extending the current understanding of the field of engineering management in technology-based organisations.

KEY WORDS
engineering management, engineering projects, decision-making, new paradigm

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Introduction

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As is the case in so many fields, the state of engineering management practice is undergoing changes in this age of uncertainty and especially in the context of the pandemic caused by COVID-19 (Baker et al., 2020). The main driver for these changes has previously included high employee turnover and changes to organisations with little historical precedence to draw from — the pandemic is simply exacerbating this situation even further. The current wave of tech-

Philbin, S. P., & Kennedy, D. (2020). Exploring the need for a new paradigm in engineering management and the decision-making process in technology-based organisations. *Engineering Management in Production and Services, 12*(4), 7-21. doi: 10.2478/emj-2020-0024

nological developments, such as those associated with Industry 4.0 (Xu et al., 2018) and the wider area relating to digitalisation (Parviainen et al., 2017) as well as the increasing interconnectedness of technologies is leading to greater levels of complexity, e.g. via system-of-systems (Lucia et al., 2016). Engineering managers are required to handle this complexity and uncertainty, and in this context, it is vital that engineering managers are equipped with effective decision-making skills. Moreover, as new technology-driven business models are adopted along with flatter organisational structures, it is increasingly the case that engineers are expected to transition into managerial and leadership roles earlier in their careers (Nittala & Jesiek, 2018). Some researchers argue that in order to cope with a higher level of complexity, organisational structures must be simplified and this can be considered through balancing the fit between simple structural solutions, complex workforce arrangements and the complex environment (Tworek et al., 2019). But from a more historical perspective, it can also be observed that throughout the time from when Taylor (1911) and Fayol (1918) developed management as an academic discipline up until the present day, there have been ongoing debates as to what actions are effective and how managers can achieve desired outcomes, i.e. the role of decision-making (Elbanna, 2006). Certain researchers proposed strategies that have gained pockets of popularity, but others question the validity of the findings.

Koontz (1960) compared understanding the competing schools to working through a "theory jungle". For example, should management dictate policy to assure best practice as stressed by Taylor (1911), or will improved performance be achieved by giving workers the freedom to determine their own best methods as indicated by the Hawthorne Experiments (Roethlisberger & Dickson, 1939). Moreover, in 1982 McGuire outlined how prevailing management theories change over time, but there is seldom a strong contender for a majority view and when there is one it does not last for very long. Rossler and Kiser (2002) lament that there is some key element missing from our understanding that might account for why certain strategies work in some situations and fail when applied in what appear to be similar circumstances elsewhere. Despite the seemingly lack of a cohesive body of knowledge, there are some hints in prior works that indicate a need for a paradigm shift (see the work of Koschmann (1996) for a comprehensive discussion on this theoretical perspective), and consequently, this article provides an exploratory analysis of this line of enquiry. Therefore, we propose that there is a pressing need for a new paradigm to be adopted for engineering management and the decision-making process.

The structure of this article is as follows. After the introduction is the second section that provides the literature review, and the third section describes the method adopted in the research study. The fourth section includes a discussion of industrial case studies. The fifth section is based on the synthesis of the research findings towards a new paradigm for engineering management and decision-making. This is followed by the conclusions and future work.

1. Literature review

1.1. Engineering management paradigm

This paper is directed at the field of Engineering Management as opposed to management in general. It is acknowledged that there is no clear division between the two disciplines that has been universally agreed upon (Lannes, 2001), but it should be noted that this research study is directed at Engineering Management in particular. To draw from one of the pioneers of Engineering Management as a recognised field, Sarchet (1989) offered that Engineering Management is specialised towards organisations dealing with processes and products of a technical nature. These organisations would have a notable contingent of their labour force employed as engineers. The narrower focus for this study is due to the proficiencies, backgrounds, and certifications of the authors. Although the topics may be applicable to the management field in general, the case studies, cited literature, and outcomes specifically deal with technical elements. The qualifications of the authors specifically to Engineering Management require a cautionary disclaimer that the applicability to management in general would require others to verify.

The concept of paradigms to define the collective understanding of a specific scientific field is attributed to Kuhn (1977). Discussions on the applicability of defining management, or Engineering Management, as science have shown such an approach to be problematic. McGuire (1982) proposed that taking an overarching view of the tracks within management theory does not yield a unified position. He also noted that the application of the existing tools often falls short of helping a manager deal with the required tasks. The lack of explicit consensus on fundamental principles within the management of knowledge workers is highlighted by Hazlett, McAdam, and Gallagher (2005) who contend the current state of the field would be best defined as a "pre-science" in Kuhn's taxonomy. Kennedy and Nur (2012) warn that focusing on prescriptive task definitions for knowledge workers creates inefficiencies in execution, but that high employee turnover appears to be driving organisations down that path. There is evidence that management practitioners would benefit from a more unified collection of theories, and many of the existing frameworks may fall short of the intent to aid managers in decision-making. This research study intends to highlight factors that may provide significant benefit to academics in developing tools to guide future practitioners. The lack of an existing unified body of knowledge hinders the presentation of modifications to improve understanding. This work intends to spur investigations in a direction that may prove highly beneficial to engineering and technology-based organisations going forward.

1.2. Historical overview

Frederick Herzberg is one of the major influencers in the development of management theory (Balzer & Smith, 1990). Much of his research was devoted to improving the quality of work and improving organisational performance as a result. Herzberg recognised that managers and academics looked to him for guidance. However, Herzberg (1966) warned that following his advice would not automatically result in the quantum shift in outcomes that his audience may be seeking. He acknowledged that the financial success of organisations is mostly determined by often one-time strategic decisions made relating to elements such as the physical location, engineering facility design and marketing strategy adopted. W. Edwards Deming is often credited with leading the move to focus on modern quality principles, including increasing the workers' ability to self-determine their processes (Phelps, Parayitam & Olson, 2007). Despite Deming's focus on quality and stressing the folly of measuring employee performance, he stated that the most important decisions determining organisational performance could be the hiring of talented workers.

Herzberg did not devote attention to the factors he listed as being the most critical because he acknowledged that these decisions are typically made long before managers find themselves in charge of their departments. He focused on the issues that managers typically have control over. Similarly, Deming did not write extensively on the hiring process and finding these talented people. Like Herzberg, Deming viewed the turnover of employees as so low that managers did not have much influence on who is actually on their team (Gabor & Tarrant, 1990). Furthermore, in Deming's time, lifelong employment at the same company was realistically expected by workers and managers. Therefore, in Deming's view, there was little point in measuring performance differences in workers since there was very little managers could do about the findings. These examples of the focus of Deming and Herzberg are offered to provide a possible explanation for the lack of study on those factors they recognised to be most influential on organisational performance.

Taylor's work supports the ideas of Deming and Herzberg that worker performance is mostly influenced by the workplace they occupy, which is analogous to the contingency theory of management, i.e. the design and implementation of control systems is dependent on the context and environment of the organisational setting (Fisher, 1998). Taylor proposed that it is the duty of management to provide the optimum tools to allow the workers to excel. Deming stated that measured variations in worker performance are most likely to be rooted in the variances in the physical system the worker occupies (Carson, Cardy & Dobbins, 1991). During the Hawthorne Experiments, Roethlisberger & Dickson (1939) recorded an analysis of the top performers as defined by the measures used by management. They were very surprised to find a negative correlation between talent (as measured by elements such as IQ and aptitude tests) and performance. The explanation given was that the reward system discouraged the better-skilled workers from achieving their full potential. All workers demonstrated a reluctance to push themselves to the maximum and the best effectively held back the most. The workers' explanation for this was that management was not aligned with supporting top performance. The most skilled workers reported that management tended to thwart their efforts and that they were generally unrecognised when they did put in any extra effort. That this was observed more than 80 years ago, hints that an opportunity was identified and appears to have had little attention paid to it over that time.

1.3. How work has changed

To quantify the order of magnitude in worker performance, Tom Peters (2004) reported that a top worker performing manual tasks might be three times better than an average, competent worker. Recognising the shift towards increasing numbers of people performing tasks with non-tangible outputs, Drucker (1959) coined the term "knowledge worker" to provide insights on how to manage such work. Peters (2004) proposed that the potential with knowledge work productivity improvements is significantly greater than manual, tangible outputs. Top knowledge workers are around seven times more productive, given that knowledge workers can eliminate unnecessary steps and still achieve the desired results. When combined with the reductions in team communication paths and supervision requirements coming from a drastic reduction in labour, a highly effective team can potentially achieve better results than a large complex organisation due to possessing a higher level of per-worker output. Moreover, Kennedy (2010) provided several examples of observed situations where these levels of output by top performers were achieved for both manual and knowledge work. In one case presented by Kennedy, not only could the one worker equal the quantity of output of six peers, but the client-reported quality of work was also superior.

There are pockets of literature examining the critical nature of top performers to organisational survival. These individuals are seen to be scarce enough that an organisation may not be able to find a suitable replacement should they lose key talent (Aguinis, Gottfredson & Joo, 2012). In what is widely considered the project management "bible" (Zhang, Kitchenham & Jeffery, 2007), Kerzner outlines how top performance comes when highly competent people are allowed to deviate from the prescriptive processes sanctioned by upper management (Kerzner, 2017). This is in contrast with Taylor's "one best way" of performing tasks that should be specified by management for the workers to follow. Taylor's strategy will likely be satisfactory for the typical worker, manual or knowledge focused. If the rare highly skilled knowledge worker is a reality, potentially game-changing results will only be realised if these workers can deviate from the way their peers are instructed to perform.

Looking at current trends, it appears the level of automated processes will increase, and the managerial toolbox previously developed under a system heavily reliant upon manual, tangible outputs per worker will decrease in suitability for future organisations (Kennedy & Philbin, 2018). As noted in the introduction, technological developments associated with Industry 4.0 (Xu et al., 2018; Krykavskyy et al., 2019; Vetrova et al., 2020; Nwaiwu et al., 2020) and the wider area of digitalisation (Parviainen et al., 2017; Afonasova et al., 2019; Siderska, 2020) can create a system highly sensitive to the decisions of a single worker. The increasing interconnectedness of technologies leads to greater levels of complexity as demonstrated by increasing interest in concepts such as system-of-systems (Lucia et al., 2016; Philbin, 2008). The potential for an increased impact on performance by single individuals is more significant to managers given the global trends for much higher employee turnover than that experienced by early researchers (Rana et al., 2009).

Despite the importance of individuals in the organisation as discussed by Herzberg, Deming and others, they spent little time discussing employee selection because of the expectation of lifelong employment for the worker (Wolff, 2008). To be better prepared for future workplaces, managers should therefore be equipped with the tools to capitalise on the dual impacts of greater sensitivity to the performance from individual workers and the high turnover of employees providing much higher incidences of opportunities than expected by the earlier researchers in management.

1.4. Recognising the impact of top performers

The rarity of those with game-changing skills has been broached by Fox (2009), when looking at mutual fund managers. Fox contends that any detailed analysis of fund performance yields that differences in managers over time cannot be shown to be anything more than random chance. Managers who have fund returns above average one year are as equally likely statistically to be below average the next as those who finished below average the prior year. As well, gross performance above the market indices is typically less than the management fees charged for the work.

This has given rise to the increase in exchange-traded index funds (ETFs) at the expense of investment in mutual funds. However, Fox notes that there will be those rare managers who are worth their fees and who will adapt their strategies to match conditions to beat random performance defined by the indices. Fox provides Warren Buffett as the most famous of these. The scarcity of these people makes it very difficult to find them among the population of their peers who do not secure statistically significant results.

It appears that the nature of the situational understanding required for these talented people to make the decisions with long-lasting impacts is not deep or overly complicated from a technical perspective. As with the example of mutual fund managers, it is more common than it should be for senior managers to not know who is providing higher-quality information. Upton (1998) provided the case in the 1980s when Kodak considered improving their chemical processes. Feedback from many employees at lower levels varied about the benefits to the proposed upgrade. The manager burdened with the final decision, ultimately decided to cancel the project in what was viewed by his superiors as a bold move. This allowed rival Fujifilm to hire Kodak's now unneeded technical experts and establish a modern plant based on the concepts of the scrapped Kodak upgraded production facility. The impact on Kodak's business resulted in losing 10% of the domestic U.S. market share within a few years with a corresponding uptake by Fujifilm. This highlights how a single decision can have billions of dollars in impact (Gavetti, 2004) and how a different person in that position could make the opposite decision given the same evidence.

In another case of when a company's swings in fortune result from a few decisions, Xerox provides evidence of how individuals can greatly impact performance. In 1999, new CEO Thoman attempted to take Xerox away from their roots as an equipment manufacturer to a provider of services. After a 90% drop in market capitalisation to under USD 300 million, Thoman was let go (Chesbrough, 2002). New CEO Anne Mulcahy returned Xerox to a focus on manufacturing and reversed the downward spiral in earnings and investor trust (Slocum, 2006). Xerox is again a solid, consistently profitable company with a market capitalisation now over USD 8 billion. The technology sector has several further high-profile examples of where decisions were taken that had a profound impact on the company — in some cases, a positive impact, and in others, a negative one. In the widely reported case for the previous market leader for video rentals, Blockbuster, once had the opportunity to acquire a major share of the startup Netflix (Sim, 2016). At the time, the CEO decided not to pursue the acquisition; within a short period of time thereafter, Blockbuster became a bankrupt company, completely losing its market dominance and being swept aside by the rapid success and growth secured by Netflix. The CEO's decision, in this case, having a catastrophic outcome for Blockbuster employees and shareholders. In terms of management theory, this is also an excellent example of the impact of creative destruction (Diamond, 2019), where the new technology-driven business model of Netflix disrupted the marketplace and ultimately led to the demise of Blockbuster.

The above examples are provided to demonstrate how individuals make decisions that are difficult to judge objectively on quantitative analysis, are not overly technical, but can have a significant and long-term impact on an organisation's performance. The authors contend that there are opportunities for these types of decisions at most levels and how they are generally not noticed by management.

2. Research methods

The method adopted in this research study is based on the process of inductive reasoning to identify specific instantiations that can be used to derive more generalised conclusions (Ketokivi & Mantere, 2010). The nature of knowledge work limits the viability of traditional deductive experimentation to arrive at a "one best method" to direct employees (Mintzberg, 1973). Mintzberg established a detailed taxonomy of possible research methods. Mintzberg demonstrated how most are difficult to use in a managerial setting and still provide reliable results that tie to the research topic. Selecting a research method becomes a process of eliminating those from the taxonomy that are not viable until few remain. As an illustrative example from this research, a quantitative analysis of a survey, according to Mintzberg, would require a thorough understanding of the complex system prior to the development of survey questions that could add insight. Mintzberg suggests that once the level of understanding is adequate for developing such surveys, the increased understanding from such a process is much lower than that acquired from the initial insights obtained through observation. We direct the reader to Mintzberg's book for a detailed analysis of further information on the selection of research methods if there is uncertainty on why an alternative research method was not selected here. The cases used for this paper occurred over several decades. The synthesis of the proposition offered developed from an initial idea stemming from reflections upon similar occurrences and returning to the cases presented here to provide the evidence that supports the position of the authors.

The main areas, as part of the methodological scheme for the research study, are depicted below

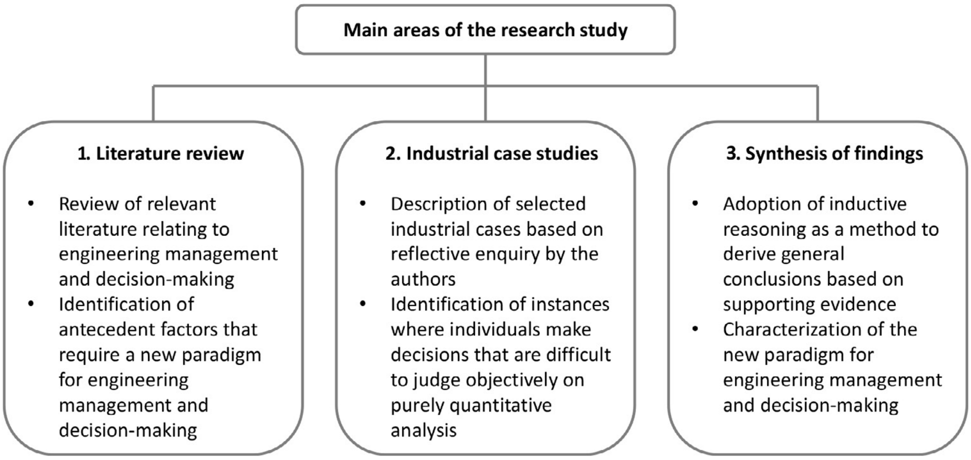

Fig. 1. Methodological scheme for the research study

(Fig. 1). The method is composed of three main stages, which are as follow: a literature review (1); industrial case studies (2); and synthesis of findings (3). This approach allows for considering relevant and pertinent literature to determine the key antecedent factors that require the adoption of a new paradigm for engineering management and decision-making. This position is explored through reflection of a series of industrial cases using the participatory action research method and a process of inductive reasoning to allow synthesis of generalised propositions that are linked to the industrial cases and antecedent factors from the literature.

3. Industrial case studies

Through their careers, the authors have been exposed to the inner workings of more than 50 organisations. There have been instances where they were fortunate to witness details that would not be available to an investigator performing a specific study as an outsider. For example, one of the authors was in a planning meeting where certain expertise in high voltage harmonics was established as needed. The experts in the room were able to identify only one person in the geographic region (population of circa 5 million) who had the necessary skill to do the required work. They proceeded to negotiate with the worker's current employer to have the worker seconded for the duration of the design schedule. These situations emerge when a very specific skillset is required. However, the authors contend that workers with rare special skills can be found for almost any job type. These are the type of workers who can make decisions that will greatly impact organisational performance. Nevertheless, these workers are also rare. At one conference attended by one of the authors, a keynote speaker speculated that exceptional workers with performance-changing skills represent around 1 in 300 workers. The authors assume that people having such skills can also use them. From the experience of the authors with many different industrial organisations, and looking deeply among the ranks, such workers are available at a frequency of around 1 in 100. It is disappointing to note that these people are too often unrecognised by management as being special and are either passed over for key positions or among the first to be let go in a downturn (Kennedy & Huston, 2012).

It is useful to consider a series of industrial cases to advance the analysis of opportunities to positively impact the role of engineering management and decision-making processes. The data for the examples that follow are taken from first-hand encounters with the participants, using the participatory action research method (Chevalier & Buckles, 2019). In each case, at least one of the authors was involved within the primary industrial organisation for a longer-term service (i.e., a minimum of several months). The observations recorded were not the focus of the work within the organisations, but rather were extracted here due to similarities of the situations relative to the subject matter being presented. All representations of the events are from first-hand involvement in the work being observed and direct discussions with the participants.

3.1. Case I: recognising an opportunity with significant impact

The first case involved an EPC (engineering, procurement and construction) company hired to design and build a process plant for an operating company. A part of the design involved numerous piping runs. The design process involved best practice stages with supervision by experienced engineers, interdisciplinary reviews, approvals by owner company engineers at various stages of design maturity and final engineer stamped drawings issued for construction.

Along with the physical design, there were process calculations, operations modelling and control logic programming. This process involved more than 100 people. At no point were any reservations raised in the proposed design. However, a part of the design proposed 14-inch piping, including fittings and valves. When a project engineer assigned to the construction of the approved facility was requested to approve the purchase order for the 14-inch valves, she raised a flag about the appropriateness of the sizing. The experienced procurement officer noticed nothing unusual because three quotes were received for the material, and the lowest was selected. The project engineer, however, was aware that 14-inch piping was not a "common" size. The design engineers selected the "standard" 14-inch sizes but herein lies the difference. Although many of the people involved in the project to this point were fully experienced in similar engineering projects, none were ever sufficiently required to consider the financial impact of their decisions.

A summary review of published literature on optimising piping designs found the inclusion of 14-inch piping as a "standard" size and an equally viable choice as 12-inch and 16-inch piping (e.g., Akbarnia, Amidpour & Shadaram, 2009). Only a rare team member who has looked at the financial impact of such decisions would know that 14-inch piping is not "common". Deviating from what is typically used, such as selecting an uncommon piping size, can have a significant and unexpected impact on the cost (Fig. 2). Once the impact of the choices was highlighted by the project engineer, modifications to the design were made substituting 12-inch valves along with other engineering changes to accommodate the hydraulic impacts. The installed cost of the project was reduced by USD 120 000, or 2% of the total project cost. In an industry where average profit margins on such projects are typically less than 5% (Silva, 2014), such savings have a notable impact on the viability of the engineering company. Again, the issue was not technically complex, but the improvement was not apparent to the first hundred people involved. It is also notable that the engineer who identified the recommended change had to expend several hours demonstrating to the other team members that the point was valid. It is also notable that a slowdown in the engineering company subsequent to these events resulted in the layoff of approximately 5% of the staff and the project engineer who identified the opportunity was one of those let go. This is offered to suggest that management may not recognise the value of such a person within their organisation.

The relevant highlights of Case I are as follow: i) a team of more than 100 people developed a plan according to their accepted work methods; ii) one person offered a more cost-effective alternative; iii) the group at large required convincing of the validity of the proposal; and iv) senior management appeared to not recognise the value of this individual.

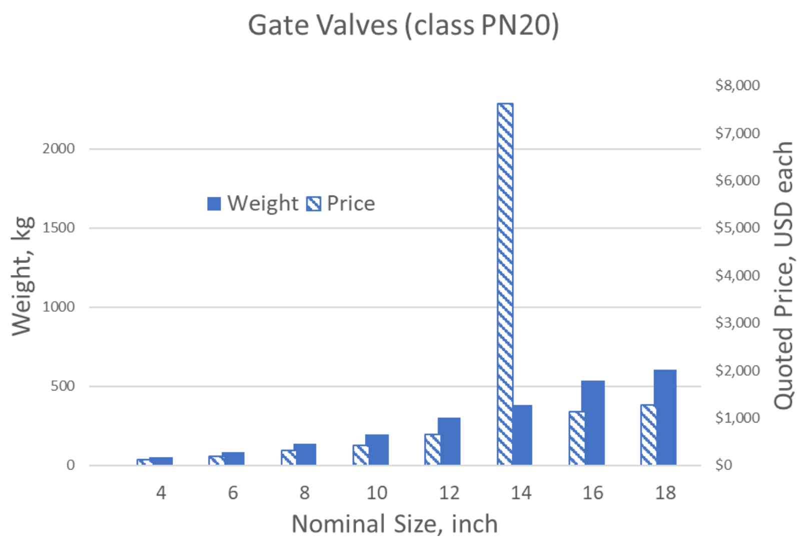

Fig. 2. Comparison of price vs weight for standard valve sizes

3.2. Case II: the impact of not clearly understanding a system

The authors contend that the types of potential benefits from Case I are more common than senior management may understand or at least acknowledge within their organisation. To demonstrate, the authors provide further illustrative examples from their industrial experiences of identifying how key individuals who have a better understanding of the factors leading to success can greatly influence outcomes. A second case involved a situation where a company decided to adopt a new ERP (enterprise resource planning) process and data management system for improved tracking of the company's history. One technology expert offered a personal opinion that the existing data could not be easily uploaded into the new ERP system, and a conversion effort was required to convert the data into a more compatible format. After expending around USD 500 000 in data conversion, an outsider to the process discovered what was being done and pointed out that the internal expert made an error as the new system had the ability to easily absorb the existing data without the conversion step.

The relevant highlights of Case II are as follow: i) an established company with thousands of employees implemented a change in knowledge work processes; ii) the in-house expert in the digital information system made a decision based on experience that needlessly expended important resources; iii) no one else in the organisation recognised the inefficiency; and iv) the management did not appear to acknowledge any suboptimal performance.

3.3. Case III: the lasting impact of plant infrastructure decisions

A third case relates to the expansion of a chemical company's operations through the development of a new storage system consisting of tankage to store liquids. The company recognised the potential for further expansion and acquired the real estate to double the number of tanks from four to eight, as shown in Fig. 2. The design team decided to place the pumps used to transfer the liquids close to the main road. Five years after the engineering facility was designed, approval was received to proceed with the expansion. The head engineer, relatively new to the company, reviewed the scope and pondered why the pumps were not placed in the middle of the eight tanks instead of at one end. The pumps do not have the ability to draw the liquid from the required distance. Adding a second set of pumps cost the company circa USD 2 million, an expenditure that would not have been necessary if they were placed as shown in the right side of Fig. 3. Such an approach was not considered at the time of the original design but had someone been on the project team who better understood engineering design, the improved design would have been selected.

As with Case II, Case III involves a decision that has significant operating and capital impacts. The highlights can be summarised as follow: i) a fully qualified and certified design team is used to design new plant infrastructure; ii) a fully qualified in-house worker evaluates the proposed design and determines a suitable location for facilities that meets all the current requirements; iii) an equally qualified person

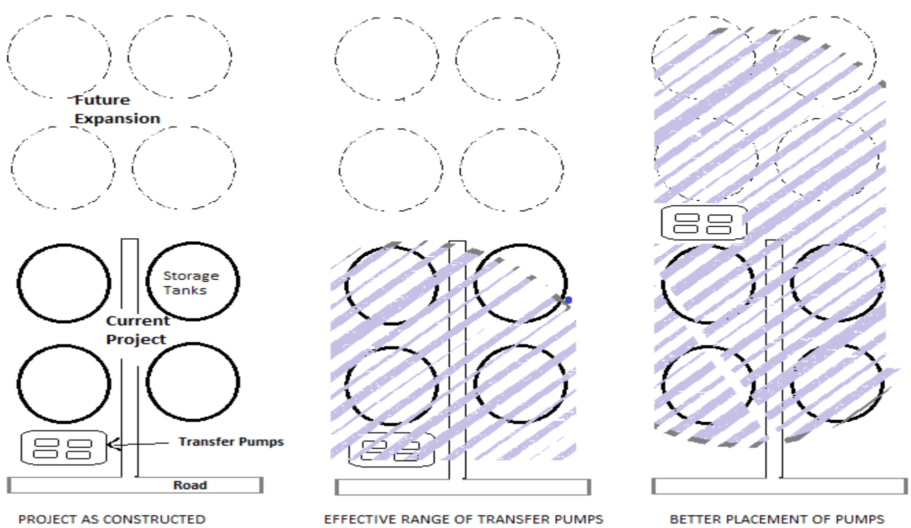

Fig. 3. Case of pump placement

then identifies how a better decision could have been made that improves operation and avoids significant future costs; and iv) the management did not acknowledge any lessons learned from the new revelations.

3.4. Case IV: the lasting impact of one-time decisions

A fourth case involved two competing open-pit mining companies, A and B, which have been operating for several decades in geographic proximity. A review of the financial reports indicates that Company A consistently has 10% lower operating costs than Company B. In speaking to geologists at both companies, they acknowledged that the difference is largely due to the locations selected for the mines. The original chief geologist for Company A selected regions to acquire where the amount of soil required to be removed was minimal. The chief geologist for Company B selected regions where the ore was richer in the product. The savings from moving much less soil gave Company A an advantage of several million dollars annually over its closest rival.

Case IV highlights Herzberg's contention that the initial design decisions can have a much greater impact on organisational viability than any of the motivational policies he championed. The relevant elements of this case can be summarised as follow: i) both companies had hundreds of engineers and support staff involved in the initial design of their facilities; ii) each company proceeded on a slightly different path in selecting the locations for their plants using fully trained and qualified people; iii) after years of operation, the decisions made by a key person proved to be significantly better for profits compared to the competing design team; and iv) published financial statements and analyses by neither company recognised the fundamental difference in the decision made at the time of design and how this affected the relative performances of the two companies.

3.5. Case V: impact from a single person deviating from prescribed policy

The fifth case involves a situation where a company incorporates advanced automation into its manufacturing assembly line, and an unfortunate fire destroyed a section of the control equipment. It was estimated that it would take about eight weeks to complete repairs to the stage where the hardware cards will be needed to be reinstalled into the control panels. The project engineer directed the purchaser to obtain the cards in four weeks to assure they arrived in time with a healthy buffer. Aiming to adhere to company protocols, the request was made explicitly by a required form, where the required date was entered as a single cell that does not allow for any leeway in the form of a range. The procurement team held vendors to the four-week deadline. This required substitution of the specified cards with another more readily available model that would provide a suboptimum solution allowing the plant to restart but with less than the desired performance. The team changed plans to accommodate the new direction, but one team member on the design team decided to telephone the vendor. It was discovered that the proper cards would be available in six weeks (within the time available to reinstall on schedule), but the vendor was not told there was some flexibility in the delivery schedule. Although the inquisitive team member was reprimanded for overstepping their area of responsibility, the company followed through with buying the desired cards. If that one team member had not taken the initiative (knowing the reprimand might come), the company would have gone down the less desirable path.

The relevant elements of Case V are as follow: i) a fully qualified and experienced team of company employees is executing a project; ii) one person oversteps their assigned duties to challenge the decision made by the team; iii) the alternate is shown to have an advantageous outcome; and iv) despite an improved outcome, the employee is reprimanded by management for not following the company policy.

3.6. Case VI: narrow focus driving decisions with long-term impacts

The sixth and final case is based on a designer with decades of experience drawing P&IDs (piping and instrumentation diagrams), who is asked for their opinion on two alternatives for a particular engineering layout and operating philosophy. The designer recommended the option that would require 40 hours to draw, noting the other option would require 160 hours to draw. When the drawings were completed, they were sent for review by several stakeholder groups. After being approved by most of the stakeholders, one operations worker noted that a solution equivalent to the rejected alternative is better because it would save an estimated USD 200 000 a year in operating costs and be simpler to maintain. The operations worker championed the alternate design and won over support for the improved design, including some dissension by the design team. The designer was then instructed to go back and produce a new set of drawings in line with the originally rejected proposal.

The elements of Case VI which parallel the previous cases are as follow: i) a fully qualified and experienced expert on design makes a decision; ii) a company with hundreds of engineers on staff reviews and accepts the decision with no questions on the design; iii) one person without experience in design offers a beneficial alternative; iv) the better alternative is not accepted immediately and encounters resistance; and v) no specific lesson was documented, or any change to company design standards was made.

3.7. Cross-case analysis

Following the recommendations of Yin (2002), a cross-case analysis is provided in Table 1. The key elements from the summaries of each case are shown in tabular form to emphasise the points being illustrated.

These cases from the industry are offered as examples of situations that have been encountered many times by the authors. As shown, many people are often fully communicated to make sure that engineering plans reach a wide set of reviewers. However, there is a small number of people whose involvement is necessary for the best choices to be made. The examples from the industry do not require a specialised area of expertise from a technical or quantitative perspective. But there is a requirement for the individual to have a more complete or systemic understanding of the success factors for the enterprise. Further, the adoption of an integrated systems view of project can allow engineers to be aware of a broader set of factors to be considered when overseeing the delivery of complex engineering projects, namely, process, technology, resources, impact, knowledge and culture (Philbin & Kennedy, 2014). Engineers able to display such a systemic perspective will benefit from considering the full range of factors and issues to be addressed when designing complex systems and engineering projects and, thereby, avoiding so-called "stove pipe" behaviour of specialists (Ireland et al., 2010), which can lead to negative outcomes associated with a reduced selection of options. Indeed, management guru Tom Peters identified a problem in modern organisations by creating a narrow focus in their workers with the result that specialists are encouraged to control a small portion of the overall operation without learning the impact it has on other departments (Kennedy, 2015). However, the high employee turnover rates now experienced in the 21st century (Cohen, Blake & Goodman, 2016), provide some opportunities mostly ignored by management studies of a few decades ago, as noted above. Firstly, managers now have many more opportunities to hire the type of special individuals identified in our exam-

Tab. 1. Cross-case analysis

No.	Element of interest	Case I	Case II	Case III	Case IV	Case V	Case VI
1	Is the initial decision-maker fully qualified and experienced in the role?	Y	Y	Y	Y	Y	Y
2	Does the decision have an impact greater than one year of the salary of the decision-maker?	Y	Y	Y	Y	Y	Y
3	Was the initial decision reviewed by competent personnel and accepted?	Y	Y	Y	Y	Y	Y
4	Does the person providing a better alternative have better identifiable qualifications or experience than the original decision-maker?	N	N	N	N	N	N
5	Was there a need for complicated mathematical calculations to identify the potential benefit?	N	N	N	N	N	N
6	Is the alternative identified in time to take corrective actions?	Y	N	N	N.A.	Y	Y
7	Was there visible recognition by management that the person providing the beneficial alternative was providing unique and valuable tacit knowledge?	N	N	N	N	N	N
8	Was there visible recognition by management that would indicate an improved decision-making process going forward?	N	N	N	N	N	N

ples. Secondly, the succession of jobs now experienced by engineering workers provides the potential to be exposed to many more circumstances and chances to learn perspectives that can be beneficial in new situations. A caution is noted here that in some of the examples reported, the workers who proposed the beneficial changes met resistance and did not receive recognition by their management or were even reprimanded in one case.

4. Towards a new paradigm for engineering management and decision-making in technology-based organisations

It can be observed from the aforementioned cases from the industry that engineers, of course, need the required skills and knowledge (Litzinger et al., 2011) gained through engineering education and subsequent on-the-job training. This includes the quantitative and mathematical skills and knowledge associated with engineering as well as other engineering aspects, such as engineering design, control engineering, materials engineering, etc. Engineers that transition into management also need to have a thorough understanding of the tools and techniques associated with managing systems, people and projects (Mitchell et al., 2019), such as organisational design, team leadership, project management and engineering economics (Philbin et al., 2019). But, crucially, there is also a need to know when to be intuitive in selecting the course of action. Such an intuition, while being guided by having the engineering and engineering management skills and knowledge, should also be a function of experience and akin to "following your gut" for a particular engineering management decision.

The question arises, how can technology-based organisations prepare for such situations? The answer is not straightforward. Essentially, organisations need to accept that following procedures, conducting quantitative assessments and adhering to sets of key performance indicators (KPIs) will only work to a point. In the absence of management controls, implementing a balanced scorecard can help the management to improve operational performance and ensure operations remain aligned with organisational strategy (Kaplan & Norton, 1996). However, there is still a need for judgement to be applied by the management. This judgement may be in the form of which KPIs are given the highest priority on achieving, or it may be a more subtle form of judgement, such as understanding how to engage stakeholders in the development of the KPIs.

Organisations can raise awareness of the benefits of adopting this holistic approach to decision-making (Savory & Butterfield, 1998), by deploying standardised and numerical-based decision frameworks alongside more intuitive and judgement-based approaches. Engineering companies can institute strategies to support how to tackle this situation. This could be in the form of workshops that seek to share experience and learning from projects. These projects would highlight how the standardised procedures and numerical assessments need to be balanced against experience-based judgements that are not always the most logical next steps. However, the projects would act as case studies that would share the learnings and drive forward best practice in organisational and project decision-making. Additionally, knowledge management systems can be implemented (Maier & Hadrich, 2011). The frequently encountered challenge with knowledge management is how to capture tacit knowledge. The capture of explicit, technical data and information is relatively easy. But capturing tacit knowledge built up over many years by knowledge-based workers is particularly difficult. However, if an effective knowledge management system can be implemented, then it may be possible to capture the experience-based insights and knowledge that can feed into future project decisions that require experience-based inputs to be considered alongside the numerical frameworks.

A supporting culture will be required to implement the aforementioned approaches, and this culture will need to accommodate risk and reward for the knowledge workers if they are to feel comfortable to take project decisions that incorporate judgement alongside numerical decision frameworks. In this regard, senior management will need to be supportive (Ribiere & Sitar, 2003) through ensuring a collaborative culture allows the organisations to effectively learn from project successes and also from mistakes. Indeed, existing project management processes stipulate that a project lessons learnt review should take place after a project has been completed and the key findings from the project should be captured and stored so that projects in the future can benefit from the insights generated from the project (Carrillo et al., 2013). However, all too often at the end of a project, the project team members move on to other projects and in some cases, even move on to other organisations before the lessons learnt can be captured. Instead, a log of lessons learnt should be kept throughout the project so as to avoid this situation. Moreover, such project lessons learnt need to be integrated into the knowledge management system so that the knowledge and insights on delivered projects are available with explicit and other forms of tacit knowledge to improve organisational and project level decision-making (Collins, 2010).

Ultimately there is a need for organisations to leverage all available resources, including the physical as well as non-physical or intangible resources (Mahoney & Pandian, 1992). Industrial companies can in some cases be adept at managing physical resources (such as infrastructure, equipment, materials as well as capital; provision), but they can be less effective at successfully managing the contributions of knowledge workers. If organisations and engineering projects are to be more effective in implementing decision-making frameworks that incorporate judgement as well as numerical assessments, facilitated by efficient knowledge management and a supportive culture, there will need to be improvements in how organisations harness the contributions of the knowledge workers.

Conclusions

The research study reported in this article has explored the need for a new paradigm for engineering management and the decision-making process. This has been enabled through consideration of key areas of the academic literature as well as drawing on the insights gained from a series of industrial cases. As a part of a process of inductive reasoning, the findings of the research study have been synthesised to identify the new paradigm for engineering management and the decision-making process. This includes several areas, which are as follow: the need for engineering managers to have enhanced professional skills and knowledge; the importance of experience-based judgement; effective knowledge management; supportive leadership and overall organisational culture; and a holistic approach to decision-making.

The authors contend that the industrial cases provided in this article are common enough and an organisation that directs resources towards the enhancement of decision-making processes can have significant improvements in viability. It should also be noted that the knowledge contained by engineers who were able to identify improvement opportunities did not involve complex calculations requiring years of study of advanced subjects. Therefore, the authors propose that the management should be able to cultivate engineers who could step up in such circumstances to help direct proper stewardship and, thereby, more effective decision-making. In this context, it will be important for engineering managers to have access to the required skills and knowledge that moves beyond the traditional background in quantitative methods. This enhanced set of skills includes people and social related abilities and awareness and can be viewed in relation to EQ or emotional quotient (Bar-On et al., 2004), i.e. an ability to manage emotions through positive engagement with others and through effective communication to address challenges that may arise.

We must also note that this is not an issue helped by most typically offered tools intended to assist engineering managers in improving performance. In all the industry cases covered, quantitative measures would not flag any problem with decisions being made. Deming often highlighted how the important factors for success were not quantifiable. In this vein, there is much literature demonstrating how quantitative measures, such as KPIs, that may lead to behaviours that are actually opposite to the outcomes intended to be supported (Paul-Hus, Desrochers, De Rijcke, & Rushforth, 2017) or even manipulation to cloud issues that may deserve management action (Demski, 1998). Indeed, Kennedy and Huston (2012) provide the case where one project manager was seen by upper management as being a top performer because his projects were consistently under budget. However, the researchers highlighted that by adopting a longer-term perspective, the engineer was able to secure higher budgets to make it easier to come in under the budget. Other project managers completed similar engineering projects spending much less, but only meeting or slightly exceeding their negotiated budgets. Looking at a sample of very similar projects, the top performer spent in excess of USD 2 million more than the other project managers for similar scopes. As a consequence of focusing on performance against negotiated budget, management rewarded the project manager's skill in effectively gaming the system rather than their overall ability to steward resources.

Future work is suggested to focus on a detailed investigation of the decision-making process that is currently adopted by engineering managers. In this regard, longitudinal research studies are recommended that examine the decision-making processes in industrial engineering companies; international comparative studies are also suggested as an informative empirical mechanism to reveal greater insights in this area. Finally, it is suggested that future research is directed towards understanding the impact of increasing levels of digitalisation on the decision-making process as well as identification of the tools and techniques available to engineering managers in this context.

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Warehouse location selection with TOPSIS group decision-making under different expert priority allocations

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ABSTRACT

Warehouses are crucial infrastructures in supply chains. As a strategic task that would potentially impact various long-term agenda, warehouse location selection becomes an important decision-making process. Due to quantitative and qualitative multiple criteria in selecting alternative warehouse locations, the task becomes a multiple criteria decision-making problem. Current literature offers several approaches to addressing the domain problem. However, the number of factors or criteria considered in the previous works is limited and does not reflect real-life decision-making. In addition, such a problem requires a group decision, with decision-makers having different motivations and value systems. Analysing the varying importance of experts comprising the group would provide insights into how these variations influence the final decision regarding the location. Thus, in this work, we adopted the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to address a warehouse location decision problem under a significant number of decision criteria in a group decision-making environment. To elucidate the proposed approach, a case study in a product distribution firm was carried out. Findings show that decision-makers in this industry emphasise criteria that maintain the distribution networks more efficiently at minimum cost. Results also reveal that varying priorities of the decision-makers have little impact on the group decision, which implies that their degree of knowledge and expertise is comparable to a certain extent. With the efficiency and tractability of the required computations, the TOPSIS method, as demonstrated in this work, provides a useful, practical tool for decision-makers with limited technical computational expertise in addressing the warehouse location problem.

KEY WORDS

warehouse, location decision, multiple criteria decision-making, TOPSIS

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Introduction

Warehouses are infrastructures where raw materials or finished goods are stored before distribution for sale (Singh et al., 2018). They serve as storage facilities for enabling the movement of products through receiving, transferring, picking, and shipping. These processes contribute to the material flows in supply chains (Singh et al., 2018). Mostly, firms have warehouses within their physical vicinities where operations are under their control. When

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demand increases, firms (e.g., manufacturing) often require additional warehouse space; however, often, the option of building a warehouse may not be possible due to high investment costs (Wutthisirisart et al., 2015). In consequence, excess inventory that cannot be stored in warehouses controlled by the firms is transferred to third-party warehouses for which the firm pays rent, as well as incur labour and transportation costs for storing items and moving them back to the central warehouse (Demirel et al., 2010). These associated costs (i.e., warehousing costs) represent 24–29% of the total logistics cost (Singh et al., 2018). Due to their role in the effective management of the supply chain and its strategic importance, selecting a warehouse location becomes a crucial task.

A suitable warehouse location enhances the profitability of the firm and reduces the risk and uncertainty of the supply chain (Dey et al., 2016). It allows managers to respond quickly to demand flexibility (Jha et al., 2018). Consequently, it improves customer satisfaction, increasing the competitive advantage of the firm (Dey et al., 2016). Thus, locating a warehouse is a crucial process as it impacts capital investment, operating expenses, and customer service, and once in place, the decision becomes almost irreversible (Singh et al., 2018). Putting in the context of a supply chain network, a warehouse determines the efficiency and speed of supply chains (Singh et al., 2018). Vlachopoulou et al. (2001) argued that warehouse location selection was not only a question of choosing sites; instead, it involved comparing local characteristics of a market with the firm's overall corporate and marketing goals. Weber (1909, 1929) first introduced the warehouse location theory. The proposed problem locates a single warehouse to minimise the total travel distance between the warehouse and a set of locally distributed customers. Since then, the attention that warehouse location obtains in the current literature has increased dramatically.

Various methods were proposed to address a warehouse location problem, generally formulated as a mathematical program with solution techniques ranging from linear programming (Brunaud et al., 2018; Vanichchinchai & Apirakkhit, 2018; You et al., 2019) to search algorithms (Klose & Görtz, 2007; Huang & Li, 2008; An et al., 2014) and heuristics (Ghaderi & Jabalameli, 2013; Guastaroba & Speranza, 2014; Ho, 2015). Although single-objective optimisation methods are reported in the current literature, the consideration of multiple criteria is a direct consequence of the warehouse location problem due to the presence of various factors in the selection process. Among the early works on this domain, Lee et al. (1980) formulated an integer goal programming to a multi-criterion warehouse selection problem. However, formal mathematical programs limit the selection process only to consider criteria that can be articulated as a mathematical expression with defined measurement systems. This drawback pre-empts a holistic real-life decision-making problem due to the existence of subjective and objective criteria (Demirel et al., 2010; Dey et al., 2016). Thus, in addressing this limitation, multi-criterion decision-making (MCDM) methods have become a popular approach in the domain literature.

In the literature, works highlighting warehouse location selection went forward by presenting defined sets of criteria commonly used in the real-life decision-making process. These works used the criteria to identify the best warehouse location among a defined set of alternative sites. This process is contextualised around the realm of an MCDM where the best alternative is chosen among a specified set, subject to multiple and even conflicting criteria. More formally, the MCDM process can be defined as evaluating the alternatives for selection or ranking, using a number of qualitative and/or quantitative criteria that have different measurement units (Özcan et al., 2011). Among several MCDM methods, the use of the ELimination Et Choice Translating REality (ELECTRE) methods, the analytic hierarchy process (AHP), and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) can be highlighted as the primary methods of use (Özcan et al., 2011). The TOPSIS method was first proposed by Hwang and Yoon (1981) with the underlying principle that the best alternative is chosen based on maximising the distance from the negative ideal solution and minimising the distance from the positive ideal solution.

It is applicable in solving decisions with a large number of criteria, similar to the ELECTRE methods (Roy, 1990; Roy, 1991). This aspect overcomes one shortcoming of the AHP — its unsuitability of handling a large number of criteria or alternatives. Using the TOPSIS method, weights are determined through normalisation. This aspect overcomes the shortcomings of ELECTRE methods of possible biased data. These advantages of the TOPSIS compared to the AHP and ELECTRE make the TOPSIS more suitable for solving huge MCDM problems involving a huge number of criteria (e.g., warehouse location selection) (Özcan et al., 2011), especially where objective or quantitative data are given (Shih et al., 2007).

Hung and Cheng (2009) identified the main advantages of the TOPSIS: (1) simple, rational, comprehensible concept, (2) intuitive and clear logic that represents the rationale of human choice, (3) ease of computation and good computational efficiency, (4) a scalar value that accounts for both the best and worst alternatives' ability to measure the relative performance for each alternative in a simple mathematical form, and (5) possibility for visualisation. However, despite these advantages, using the TOPSIS method in solving a warehouse selection problem has limited insights. To the best of our knowledge, only Özcan et al. (2011), Roh et al. (2015), Büyüközkan and Uztürk (2017), and Roh et al. (2018) have explored such an approach. The TOPSIS method is applicable in solving MCDM problems with a large number of criteria, which was not explored in previous warehouse selection studies as a generic set of criteria was mostly used. Whereas in real-life decision-making, this domain problem requires a decision over a broad set of criteria. Additionally, a committee or a group of high-level managers of an organisation (or firm) along with external consultants or experts play an important role in the warehouse location selection problem (Dey et al., 2016). This expert group carefully chooses the right combination of selection criteria for the decision problem, along with important judgment elicitations necessary for the selection process. However, the obviously varied knowledge and expertise of these experts, have a significant impact on the overall group decision. Nevertheless, the current domain literature within the TOPSIS method fails to address this condition. Thus, the motivation of this study is to explore a warehouse selection problem involving a large number of criteria in a group decision-making environment, which is seen as a more realistic approach in warehouse location decision-making. The comprehensive criteria set is obtained by consolidating the significant criteria derived from the literature. In addition, of the varying importance of the analysis by experts comprising the group is put forward to provide insights into how these variations influence the final decision regarding the location. The contribution of this work is to carry out a group warehouse selection problem under a large number of criteria, which reflects real-life decision-making.

This paper is organised as follows. Section 2 presents some preliminary information on the approaches of warehouse location and the computational process of TOPSIS. Section 3 discusses the background of the case study and the proposed procedure. The insights of the findings are highlighted in Section 4. It ends with a conclusion and discussion of future work in Section 5.

1. Preliminaries

1.1. Approaches to warehouse location selection

Due to the finite number of location alternatives, usually pre-defined in the decision problem, to be evaluated under multiple, even conflicting criteria, the warehouse location selection could be appropriately framed as a multi-criterion decision-making (MCDM) problem (Özcan et al., 2011). As ill-defined formulations, MCDM problems often contain a criterion or criteria, from the set of criteria, which are subjective, with non-sharp information and limited measurement systems (Ocampo & Clark, 2015). The presence of both quantitative and qualitative factors (i.e., criteria) in the warehouse location selection process (Demirel et al., 2010) increases the complexity of the decision problem. As such, a decision regarding the location of a warehouse is generally one of the most critical and strategic decisions in logistics management and supply chain planning, mainly that such decision involves substantial capital investments and impacts future long-term capacity and inventory decisions (Demirel et al., 2010).

In a recent review by Yap et al. (2019) on the application of MCDM methods in site selection problems, to which warehouse location selection belongs, the analytic hierarchy process (AHP) of Saaty (1980) emerges as the widely used approach. In fact, one of the earliest works on solving warehouse location selection problem via MCDM methods was presented by Korpela and Tuominen (1996), with the AHP as their approach. Since then, the domain literature on this topic has flourished, and an increasing number of works that implemented MCDM methods and their hybrid, including their extensions via the use of fuzzy set theory, has been reported for the last decade. Some MCDM methods which were adopted in addressing the warehouse selection problem and closely related problems include approaches (i.e., pure or hybrid) based on the AHP (Alberto, 2000; García et al., 2014; Boltürk et al., 2016; Raut et al., 2017; Kabak & Keskin, 2018; Hakim & Kusumastuti, 2018; Singh et al., 2018; Franek & Kashi, 2017; Nevima & Kiszová, 2017), analytic network process — the generalisation of the AHP (Cheng et al., 2005), simple additive weighting (Chou et al., 2008; Dey et al., 2013), PROMETHEE II (Athawale et al., 2012), ELECTRE-II (He et al., 2017), the Choquet integral (Demirel et al., 2010), TOPSIS (Chu, 2002), VIKOR (Kutlu Gündoğdu & Kahraman, 2019), and cloud-based design optimisation (Temur, 2016), among others. Some works on this domain purposely combined two or more MCDM methods to overcome and complement the limitations of each technique and come up with a more powerful hybrid selection tool. In most cases, a different approach is adopted to address the prioritisation (or weighting) of the criteria and another tool for the ranking of alternative warehouse locations. These works include the integration of fuzzy TOPSIS-SAW-MOORA (Dey et al., 2016), fuzzy AHP-TOPSIS (Roh et al., 2018), and stochastic AHP and fuzzy VIKOR (Emeç & Akkaya, 2018). Note that this list is not intended to be comprehensive.

Aside from MCDM techniques, different methods have been explored in addressing warehouse selection decisions. In general, these techniques are associated with mathematical programming, with various solution techniques such as search algorithms and heuristics (Tyagi & Das, 1995; Rosenwein, 1996). An early work of Lee et al. (1980) first proposed an integer goal programming formulation for a multi-criterion warehouse location problem. Since then, various extensions have been developed, including mixed-integer linear programming (Kratica et al., 2014; Brunaud et al., 2018; Vanichchinchai & Apirakkhit, 2018; You et al., 2019), non-linear programming (Monthatipkul, 2016), multi-objective optimisation model (Xifeng et al., 2013), and second-order cone programming (Wagner et al., 2009), among others. Due to the complexity of the formulation, and entrapment to the local optima as a direct consequence, various techniques were developed, such as the Lagrangian relaxation approach (Ozsen et al., 2008; Nezhad et al., 2013), approximation algorithms (Huang & Li, 2008), local search algorithm (Cura, 2010), branch-and-price algorithm (Klose & Görtz, 2007), hybrid firefly-genetic algorithm (Rahmani & MirHassani, 2014), evolutionary multi-objective optimisation (Rakas et al., 2004), two-stage robust models and algorithms (An et al., 2014), and weighted Dantzig-Wolfe decomposition and the path-relinking combined method (Li et al., 2014). Search heuristics were also proposed, including hybrid multi-start heuristic (Resende & Werneck, 2006), a discrete variant of unconscious search (Ardjmand et al., 2014 and Kratica et al., 2014), math heuristic (Rath & Gutjahr, 2014), greedy heuristic and fix-and-optimise heuristic (Ghaderi & Jabalameli, 2013), kernel search heuristic (Guastaroba & Speranza, 2014), iterated tabu search heuristic (Ho, 2015), modified Clarke and Wright savings heuristic (Li et al., 2015), and swarm intelligence based on sample average approximation (Aydin & Murat, 2013). Interpretive structural modelling was also adopted to solve a warehouse selection problem that incorporates the sustainability agenda (Jha et al., 2018). When formal mathematical programs are used to address warehouse location decisions, the factors are expected to be quantitative and measurable in such a way that they can be expressed as formal mathematical equations or inequalities. However, in most real-life cases, some factors relevant in the decision domain (e.g., quality of life, social and cultural, security) are qualitative and subjective, which could not be expressed as mathematical statements. Thus, MCDM methods are considered a holistic approach in addressing both quantitative and qualitative factors in the selection of a warehouse location.

1.2. TOPSIS — the Technique of Order Preference Similarity to the Ideal Solution

In the context of MCDM applications for the selection of a warehouse location, the AHP, ELECTRE, and TOPSIS can be highlighted as the primary methods (Özcan et al., 2011). Özcan et al. (2011) made a comparative assessment of these methods, and the result is presented in Appendix 1. The assessment provides an insight into the performance of these methods in several areas. It is noteworthy that the TOPSIS has three main leverages: (1) the number outranking relations is one, which implies efficiency in judgment elicitations, (2) it is able to handle a large number of alternatives and criteria with objective and quantitative data, and (3) it generates a global, net order. These characteristics are appropriate in addressing a warehouse location selection, particularly when the number of criteria and alternatives is large, and the efficiency in generating the results from judgment elicitations is given a priority.

Initially proposed by Hwang and Yoon (1981), the foundation of TOPSIS lies at the notion of the distance function where the best alternative is chosen on the basis of maximising the distance from the negative ideal solution and minimising the distance from the positive ideal solution. Aside from location decision problems, TOPSIS has been used in a broad application domain, such as performance evaluation with the use of financial investment decisions (Kim et al., 1997), and financial ratios (Deng et al., 2000), personnel selection (Kelemenis & Askounis, 2010), strategy formulation (Ocampo, 2019), among others. Note that this list is not intended to be comprehensive. Reviews on the applications of TOPSIS have been reported by Behzadian et al. (2012), Shukla et al. (2017), and Yadav et al. (2018). TOPSIS leverages its advantages on simplicity and the tractability of the notion of distance based on ranking a set of alternatives (Chou et al. 2008; Özcanet al., 2011). It has efficient computational requirements due to its more straightforward evaluation techniques (Chou et al., 2008; Özcan et al., 2011; Roszkowska, 2011; Vavrek et al., 2017; Stankevičienė & Nikanorova, 2020).

The computational steps of the TOPSIS approach are provided below.

Step 1: Establish a decision matrix to evaluate the alternatives (e.g., supplier selection attributes) under different criteria. The structure of the evaluation can be expressed as follows:

$$D^k = \begin{pmatrix} f_{11}^k & f_{12}^k & \cdots & f_{1n}^k \\ f_{21}^k & f_{22}^k & \cdots & f_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1}^k & f_{m2}^k & \cdots & f_{mn}^k \end{pmatrix} \quad (1)$$

where f_{ij}^k, $i = 1, \dots, m$, $j = 1, \dots, n$, $k = 1, \dots, M$, represents the evaluation score on the performance (or relevance) of the ith alternative on the jth criterion, elicited by the kth decision-maker.

Step 2: Aggregate the individual decision matrices using an aggregation function. One of the highly adopted aggregation functions is the arithmetic mean. Thus, the aggregate score f_{ij} can be obtained as $f_{ij} = \sum_{k=1}^{M} f_{ij}^k$. The resulting aggregate decision matrix is shown in Equation (2).

$$D = \begin{pmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1} & f_{m2} & \cdots & f_{mn} \end{pmatrix} \quad (2)$$

Step 3: Obtain the priority weights of the criteria. The priority weight of a criterion j is expressed as w_j. Any prioritisation technique generates this. Note that the TOPSIS approach provides no specific method for obtaining the priority weights of the criteria.

Step 4: Calculate the normalised decision matrix $R = (r_{ij})_{m\times n}$. The normalised value r_{ij} is obtained as:

$$r_{ij} = \frac{f_{ij}}{\left(\sum_{i=1}^{m} f_{ij}^2\right)^{\frac{1}{2}}} \quad \forall i = 1, \dots, m, j = 1, \dots, n \quad (3)$$

Step 5: Calculate the weighted normalised decision matrix $V = (v_{ij})_{m\times n}$. Each element denoted as v_{ij}, is obtained by

$$v_{ij} = r_{ij} \times w_j \quad \forall i = 1, \dots, m, j = 1, \dots, n \quad (4)$$

Step 6: Determine the positive ideal solution (PIS), denoted by V^+, and the negative ideal solution (NIS), denoted by V^-:

$$V^+ = \{v_1^+, \dots, v_n^+\} = \left\{\left(\max_i v_{ij} : j \in J_1\right), \left(\min_i v_{ij} : j \in J_2\right)\right\} \quad (5)$$

$$V^- = \{v_1^-, \dots, v_n^-\} = \left\{\left(\min_i v_{ij} : j \in J_1\right), \left(\max_i v_{ij} : j \in J_2\right)\right\} \quad (6)$$

where J_1 is associated with the benefit (i.e., maximising) criteria, and J_2 is associated with the cost (i.e., minimising) criteria.

Step 7: Calculate the separation measures, using the m-dimensional Euclidean distance. The separation measure D_i^+ of each alternative i from the PIS is given as

$$D_i^+ = \left\{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2\right\}^{\frac{1}{2}} \quad \forall i = 1, \dots, m \quad (7)$$

Similarly, the separation measures D_i^- of each alternative from the NIS is as follows:

$$D_i^- = \left\{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2\right\}^{\frac{1}{2}} \quad \forall i = 1, \dots, m \quad (8)$$

Step 8: Calculate the relative closeness to the ideal solution and rank the alternatives in descending order. The relative closeness coefficient of the alternative j with respect to PIS V^+ can be expressed as:

$$C_i = \frac{D_i^-}{D_i^- + D_i^+} \quad \forall i = 1, \dots, m \quad (9)$$

2. Proposed procedure: TOPSIS group decision-making for the problem of warehouse location selection

2.1. Case-study background

ABC-G Enterprises is a product distributor of one of the largest brewing companies in the Philippines. It is a local distributor which is located in Cebu, an island in the central Philippines. With an increasing trend for the demand for their products, the company is in the process of finding a new location where they can build their second warehouse. The new warehouse is intended to stock a significant volume of their products to respond to an expected increase in customer demand. Two possible location alternatives were identified by ABC-G Enterprises. One possible location is at a 10-kilometre distance from their current headquarters, with an area of around 380 square meters. The second alternative has an area of approx. 300 square meters and is located within a 9-kilometre distance. Aside from the available area and the distance of the possible location, the company is also considering other salient criteria. For brevity, we refer to Talamban warehouse and Compostela warehouse for the first and second alternative, respectively. In determining the best location, the final decision lies with the administration team, which is composed of the President, Administration Manager, Senior Manager, and Assistant Manager, who are usually involved in making the crucial decisions of the company. Thus, there is a need for ABC-G Enterprises to carry out an analytic multi-criterion group decision-making process to identify the best location for the warehouse.

2.2. Computational steps

The proposed TOPSIS group decision-making process in this work consists of the following steps:

Step 1: Set up the decision warehouse location selection problem.

The decision problem is shown in Fig. 1. It shows the evaluation of two alternative warehouses (i.e., Talamban Warehouse and Compostela Warehouse) under 22 selection criteria. Current literature offers a number of selection criteria for warehouse location selection. Appendix 2 presents the majority of these criteria. These criteria are generic to some extent but may not be applicable in some cases, depending on the decision problem under consideration. The two warehouse location alternatives are evaluated with this set of criteria. Table 1 presents these criteria, corresponding codes for the brevity of presentation, and a brief description.

Step 2: Assign the importance weights of the expert decision-makers.

For this work, the administration team, which is composed of four members, becomes the expert group tasked to elicit judgments within the TOPSIS approach. Thus, the proposed approach becomes a TOPSIS group decision-making problem. However, in this case, the members of the expert group are non-

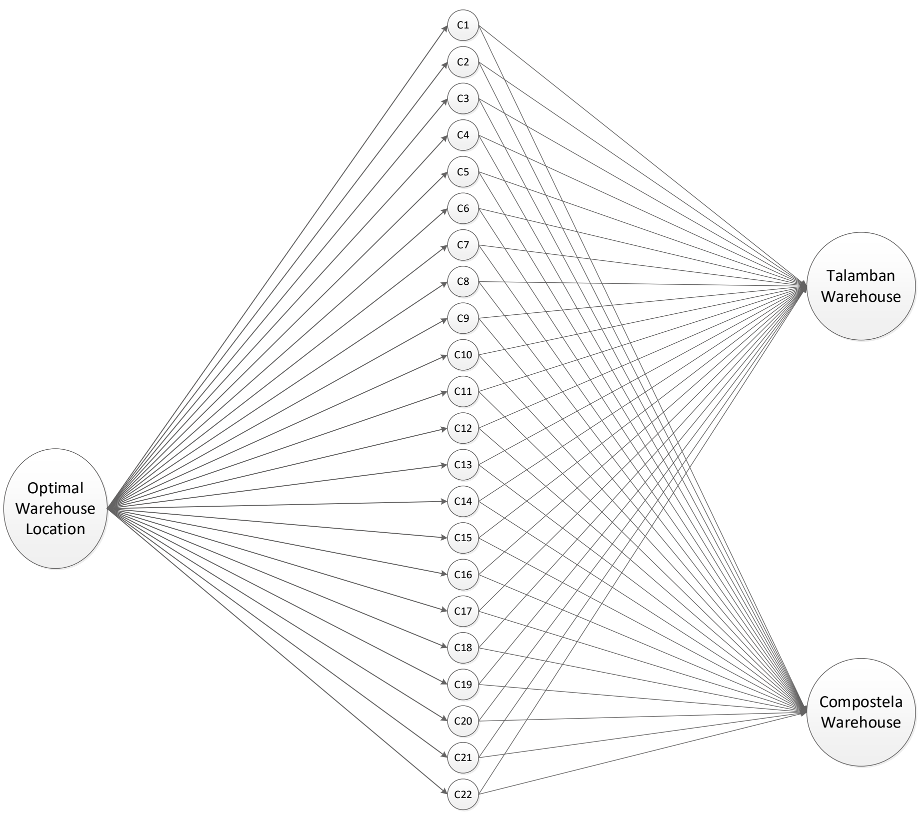

Fig. 1. Case for the problem of the warehouse location selection

Tab. 1. The set of criteria for the case of warehouse location selection

Code	Criteria	Description
C1	Unit price	Refers to the unit price per square metre of land
C2	Transportation cost	Relates to costs associated with the transportation facilities, and alternative transportation types
C3	Logistics cost	Relates to the costs of transferring products from the warehouse to their destinations
C4	Proximity to the leading supplier	The distance from the warehouse to the main supplier
C5	Proximity to customers	The distance from the warehouse to the customers
C6	Availability of customers	Number of customers in the area of the warehouse
C7	Space availability	Adequate space should be available for the warehouse
C8	Accessibility to the road	Road infrastructure considering the trucking service and road conditions
C9	Accessibility to the seaport	Considers accessibility to the seaport and distance from the warehouse
C10	Accessibility to the airport	Considers accessibility to the airport and distance from the warehouse
C11	Existence of modes of transportation	Availability of different transportation types in the location
C12	Quality and reliability of modes of transportation	Transportation service between the customer, supplier, and the warehouse
C13	Telecommunication systems	Communication facilities and technologies of the warehouse
C14	Zoning and construction plan	Different development plans, implementations, and arrangements of local administrations at alternative locations
C15	Industrial regulations laws	Various laws and arrangements at the alternative locations
C16	Security of region	Refers to the rate of loss by robbery, presence of organised crime, security personnel, and security systems
C17	Traffic access	Refers to the capacity of handling a large volume of traffic and providing ease of access to transportation infrastructure and traffic-related services
C18	Political stability	Relates to political change or stable political decisions
C19	Social stability	Risk of protests against the government
C20	Economic stability	A significant level of output growth and low and stable inflation
C21	Impact on ecological landscape	Maintains or improves the original landscape without damaging the city's image
C22	Condition of public facilities	Requires public goods, such as roads, communication, power supply, and water to function properly

Tab. 2. Rating scale for each criterion

Scale	Equivalent rating score
Very important	10
Fairly important	9
Important	7
Slightly important	5
Least important	3
Not important at all	1
Intermediate values between the two adjacent judgments	2, 4, 6, 8

Tab. 3. Importance weights of decision-makers based on S1, S2, S3

Decision-makers	Priority weights of decision-makers based on		
	S1	S2	S3
President	0.2258	0.2903	0.2500
Administration Manager	0.2258	0.2581	0.2500
Senior Manager	0.2581	0.2258	0.2500
Assistant Manager	0.2903	0.2258	0.2500

homogeneous in their expertise of the decision problem, as well as their power in decision-making within the company. Thus, the aggregation described in Step 2 must be revised. Instead, expert decision-makers are assigned corresponding priority weights. These weights represent the importance of their inputs to the group decision. One crucial point that must be addressed in the process of generating these weights. To address this, three possible scenarios were explored; that is, three sets of priority weights of decision-makers were generated. Priority weights were obtained based on (S1) the level of their expertise in warehouse location selection, (S2) their power in making decisions, (S3) equal weights. Table 2 provides the rating scale that was used to generate the importance weights of the decision-makers. The weights of the decision-makers based on the three scenarios (i.e., S1, S2, S3) are shown in Table 3.

Based on S1, the Assistant Manager got the highest priority since it has a better knowledge of the warehouse operations. The S2 scenario yields the President's judgments with the highest weight as it has the most significant power in making decisions for the company. Finally, Table 3 shows with equal priority weights, that the level of influence of the four decision-makers on the warehouse location selection is equal.

Step 3: Generate the priority weights of the criteria. Decision-makers were asked to rate the importance of each criterion on a scale from 1 to 10, where 1 and 10 representing the lowest and highest importance, respectively. With S1, S2, and S3, three sets of priority weights were also generated for the criteria set. Table 4 presents the criteria weights on the three different scenarios.

Tab. 4. Criteria weights for S1, S2, and S3

Criteria	President	Admin Manager	Senior Manager	Assistant Manager	Weights for S1	Weights for S2	Weights for S3
C1	10	10	10	10	0.0758	0.0759	0.0759
C2	9	8	9	9	0.0665	0.0663	0.0664
C3	6	5	7	6	0.0457	0.0453	0.0455
C4	9	9	10	10	0.0724	0.0717	0.0721
C5	8	8	9	10	0.0670	0.0659	0.0664
C6	7	6	7	7	0.0514	0.0512	0.0512
C7	8	8	7	9	0.0609	0.0607	0.0607
C8	8	9	7	9	0.0626	0.0627	0.0626
C9	3	1	2	1	0.0130	0.0137	0.0133
C10	1	2	1	1	0.0093	0.0095	0.0095
C11	5	5	4	5	0.0360	0.0362	0.0361
C12	7	8	8	9	0.0612	0.0602	0.0607
C13	7	6	6	5	0.0450	0.0460	0.0455
C14	4	3	4	2	0.0242	0.0250	0.0247
C15	6	7	6	7	0.0494	0.0492	0.0493
C16	8	7	7	8	0.0570	0.0570	0.0569
C17	8	8	9	9	0.0648	0.0641	0.0645
C18	5	5	4	3	0.0316	0.0328	0.0323
C19	4	2	3	2	0.0205	0.0213	0.0209
C20	4	3	3	3	0.0245	0.0250	0.0247
C21	1	1	2	1	0.0095	0.0093	0.0095
C22	6	7	6	8	0.0516	0.0509	0.0512

Table 4 shows the weights of each criterion for all scenarios, i.e., S1, S2, and S3. It must be noted that the weights of the criteria presented in Table 4 are aggregate weights concerning the corresponding importance of the decision-makers in each scenario, as shown in Table 3. For instance, the weight of C1 for S1, written as w_1^{S1}, is computed using the following:

$$w_1^{S1} = \frac{\sum_k x_{1k}^{S1} \omega_k^{S1}}{\sum_j \sum_k x_{jk}^{S1} \omega_k^{S1}} \quad (10)$$

where w_1^{S1} denotes the weight of criterion 1 in S1, x_{1k}^{S1} is the score of criterion 1 under S1 as elicited by decision-maker k, and ω_k^{S1} represents the weight of decision-maker k under S1. For instance,

$$w_1^{S1} = \frac{(10\times0.2258)+(10\times0.2258)+(10\times0.2581)+(10\times0.2903)}{131.8710} = 0.0758$$

Step 4: Decision-makers elicit judgments on the decision matrix. Using the rating scale for cost criteria (i.e., Table 5), and benefit criteria (i.e., Table 6), decision-makers elicit judgments on the performance of the jth alternative (i.e., warehouse) on the ith criterion.

The decision matrix is shown in Table 7.

Step 5: Generate aggregate decision matrices. Three aggregate decision matrices were generated, which corresponded to S1, S2, and S3 scenarios. Since the decision-makers had different importance weights at different scenarios, the aggregation function described in Step 2 of Section 2.2 had to be revised. To incorporate the importance weights of the decision-makers, the aggregation function is developed in Equation (11).

$$f_{ij}^{\sigma} = \frac{1}{4} \sum_k f_{ij}^{k,\sigma} \omega_k^{\sigma} \quad (11)$$

where f_{ij}^{σ} represents the aggregate performance score of the ith alternative (i.e., warehouse) with respect to jth criterion, under scenario σ (i.e., S1, S2, S3), $f_{ij}^{k,\sigma}$ is the score of the ith alternative with respect to jth criterion, under scenario σ evaluated by the kth decision-maker, and ω_k^{σ} is the importance weight of decision-maker k under scenario σ. The aggregate decision matrices are shown in Table 8.

For instance, using Equation (11), the value of f_{11}^{S1} can be obtained:

$$f_{11}^{S1} = \frac{(4 \times 0.2258) + (5 \times 0.2258) + (5 \times 0.2580) + (4 \times 0.2932)}{4} = 1.1210$$

Step 6: Calculate the normalised decision matrices. Using Equation (3), the normalised decision matrices are obtained.

Step 7: Calculate the weighted normalised decision matrices. Using Equation (4) with inputs from the priority weights of the criteria under the different scenarios, the weighted normalised decision matrices are obtained. Table 10 presents these matrices.

Step 8: Determine V^+ and V^- for S1, S2, and S3.

The PIS (V^+) and the NIS (V^-) are obtained using Equation (5) and Equation (6), respectively. Table 11 describes these values.

Step 9: Generate the separation measures D_i^+ and D_i^-. The separation measures D_i^+ and D_i^- are obtained using Equation (7) and Equation (8), respectively. The results are shown in Table 12.

Tab. 5. Rating scale for the cost criteria

Scale	Rating
Very Poor (VP)	10
Poor (P)	9
Medium Poor (MP)	7
Fair (F)	5
Good (G)	3
Very Good (VG)	1
Intermediate values between the two adjacent judgments	8, 6, 4, 2

Tab. 6. Rating scale for the benefit criteria

Scale	Rating
Poor (P)	1
Medium Poor (MP)	3
Fair (F)	5
Medium Good (MG)	7
Good (G)	9
Very Good (VG)	10
Intermediate values between the two adjacent judgments	2, 4, 6, 8

Tab. 7. Decision matrix

Criteria	President		Administration Manager		Senior Manager		Assistant Manager	
	Talamban	Compostela	Talamban	Compostela	Talamban	Compostela	Talamban	Compostela
C1	4	3	5	4	5	3	4	3
C2	3	4	4	5	3	5	3	4
C3	3	4	4	5	3	5	3	4
C4	9	1	1	9	9	1	8	1
C5	9	7	9	6	9	7	10	6
C6	9	7	9	6	9	7	10	6
C7	9	10	8	9	8	10	7	8
C8	9	10	9	10	10	8	9	10
C9	1	1	1	1	1	1	1	1
C10	1	1	1	1	1	1	1	1
C11	9	9	9	9	9	9	10	10
C12	9	9	9	9	9	9	10	10
C13	10	10	9	9	9	9	10	10
C14	5	9	4	9	5	9	4	9
C15	5	9	4	9	9	5	4	9
C16	8	9	8	9	8	7	4	9
C17	4	7	4	7	5	7	4	8
C18	8	8	8	8	8	8	9	9
C19	9	9	8	9	7	9	9	9
C20	10	7	1	6	10	7	9	6
C21	10	10	10	10	10	10	9	9
C22	10	10	9	9	9	9	10	10

Tab. 8. Aggregate decision matrices

Criteria	S1		S2		S3	
	Talamban	Compostela	Talamban	Compostela	Talamban	Compostela
C1	1.1210	0.8065	1.1210	0.8145	1.1250	0.8125
C2	0.8065	1.1210	0.8145	1.1210	0.8125	1.1250
C3	0.8065	1.1210	0.8145	1.1210	0.8125	1.1250
C4	1.7258	0.7016	1.6774	0.7661	1.6875	0.7500
C5	2.3226	1.6210	2.3065	1.6290	2.3125	1.6250
C6	2.3226	1.6210	2.3065	1.6290	2.3125	1.6250
C7	1.9839	2.2984	2.0161	2.3226	2.0000	2.3125
C8	2.3145	2.3710	2.3065	2.3871	2.3125	2.3750
C9	0.2500	0.2500	0.2500	0.2500	0.2500	0.2500
C10	0.2500	0.2500	0.2500	0.2500	0.2500	0.2500
C11	2.3226	2.3226	2.3065	2.3065	2.3125	2.3125
C12	2.3226	2.3226	2.3065	2.3065	2.3125	2.3125
C13	2.3790	2.3790	2.3790	2.3790	2.3750	2.3750
C14	1.1210	2.2500	1.1290	2.2500	1.1250	2.2500
C15	1.3790	1.9919	1.3548	2.0242	1.3750	2.0000
C16	1.7097	2.1210	1.7742	2.1371	1.7500	2.1250
C17	1.0645	1.8226	1.0565	1.8065	1.0625	1.8125
C18	2.0726	2.0726	2.0565	2.0565	2.0625	2.0625
C19	2.0645	2.2500	2.0726	2.2500	2.0625	2.2500
C20	1.9194	1.6210	1.8629	1.6290	1.8750	1.6250
C21	2.4274	2.4274	2.4435	2.4435	2.4375	2.4375
C22	2.3790	2.3790	2.3790	2.3790	2.3750	2.3750

Tab. 9. Normalised decision matrices

Criteria	S1		S2		S3	
	Talamban	Compostela	Talamban	Compostela	Talamban	Compostela
C1	0.8118	0.5840	0.8090	0.5878	0.8107	0.5855
C2	0.5840	0.8118	0.5878	0.8090	0.5855	0.8107
C3	0.5840	0.8118	0.5878	0.8090	0.5855	0.8107
C4	0.9264	0.3766	0.9096	0.4154	0.9138	0.4061
C5	0.8200	0.5723	0.8168	0.5769	0.8182	0.5749
C6	0.8200	0.5723	0.8168	0.5769	0.8182	0.5749
C7	0.6534	0.7570	0.6555	0.7552	0.6542	0.7564
C8	0.6985	0.7156	0.6949	0.7192	0.6976	0.7165
C9	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C10	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C11	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C12	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C13	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C14	0.4459	0.8951	0.4485	0.8938	0.4472	0.8944
C15	0.5692	0.8222	0.5562	0.8310	0.5665	0.8240
C16	0.6276	0.7786	0.6388	0.7694	0.6357	0.7719
C17	0.5043	0.8635	0.5048	0.8632	0.5057	0.8627
C18	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C19	0.6761	0.7368	0.6775	0.7355	0.6757	0.7372
C20	0.7640	0.6452	0.7528	0.6583	0.7557	0.6549
C21	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071
C22	0.7071	0.7071	0.7071	0.7071	0.7071	0.7071

Tab. 10. Weighted normalised decision matrices

Criteria	S1		S2		S3	
	Talamban	Compostela	Talamban	Compostela	Talamban	Compostela
C1	0.0616	0.0443	0.0614	0.0446	0.0615	0.0444
C2	0.0389	0.0540	0.0390	0.0537	0.0389	0.0538
C3	0.0267	0.0371	0.0266	0.0366	0.0267	0.0369
C4	0.0671	0.0273	0.0652	0.0298	0.0659	0.0293
C5	0.0550	0.0384	0.0538	0.0380	0.0543	0.0382
C6	0.0421	0.0294	0.0418	0.0295	0.0419	0.0295
C7	0.0398	0.0461	0.0398	0.0458	0.0397	0.0459
C8	0.0437	0.0448	0.0435	0.0451	0.0437	0.0449
C9	0.0092	0.0092	0.0097	0.0097	0.0094	0.0094
C10	0.0066	0.0066	0.0068	0.0068	0.0067	0.0067
C11	0.0254	0.0254	0.0256	0.0256	0.0255	0.0255
C12	0.0432	0.0432	0.0426	0.0426	0.0429	0.0429
C13	0.0318	0.0318	0.0325	0.0325	0.0322	0.0322
C14	0.0108	0.0217	0.0112	0.0223	0.0110	0.0221
C15	0.0281	0.0406	0.0274	0.0409	0.0280	0.0407
C16	0.0358	0.0444	0.0364	0.0439	0.0362	0.0439
C17	0.0327	0.0560	0.0324	0.0554	0.0326	0.0557
C18	0.0223	0.0223	0.0232	0.0232	0.0228	0.0228
C19	0.0139	0.0151	0.0144	0.0157	0.0141	0.0154
C20	0.0187	0.0158	0.0188	0.0164	0.0186	0.0162
C21	0.0067	0.0067	0.0066	0.0066	0.0067	0.0067
C22	0.0365	0.0365	0.0360	0.0360	0.0362	0.0362

Tab. 11. V^{+} and V^{-} for S1, S2, and S3

Criteria	S1		S2		S3	
C1	0.0443	0.0616	0.0446	0.0614	0.0444	0.0615
C2	0.0389	0.0540	0.0390	0.0537	0.0389	0.0538
C3	0.0267	0.0371	0.0266	0.0366	0.0267	0.0369
C4	0.0671	0.0273	0.0652	0.0298	0.0659	0.0293
C5	0.0550	0.0384	0.0538	0.0380	0.0543	0.0382
C6	0.0421	0.0294	0.0418	0.0295	0.0419	0.0295
C7	0.0461	0.0398	0.0458	0.0398	0.0459	0.0397
C8	0.0448	0.0437	0.0451	0.0435	0.0449	0.0437
C9	0.0092	0.0092	0.0097	0.0097	0.0094	0.0094
C10	0.0066	0.0066	0.0068	0.0068	0.0067	0.0067
C11	0.0254	0.0254	0.0256	0.0256	0.0255	0.0255
C12	0.0432	0.0432	0.0426	0.0426	0.0429	0.0429
C13	0.0318	0.0318	0.0325	0.0325	0.0322	0.0322
C14	0.0217	0.0108	0.0223	0.0112	0.0221	0.0110
C15	0.0406	0.0281	0.0409	0.0274	0.0407	0.0280
C16	0.0444	0.0358	0.0439	0.0364	0.0439	0.0362
C17	0.0560	0.0327	0.0554	0.0324	0.0557	0.0326
C18	0.0223	0.0223	0.0232	0.0232	0.0228	0.0228
C19	0.0151	0.0139	0.0157	0.0144	0.0154	0.0141
C20	0.0187	0.0158	0.0188	0.0164	0.0186	0.0162
C21	0.0067	0.0067	0.0066	0.0066	0.0067	0.0067
C22	0.0365	0.0365	0.0360	0.0360	0.0362	0.0362

Tab. 12. The separation measures and the relative closeness coefficients

	S1		S2		S3	
	Talamban	Compostela	Talamban	Compostela	Talamban	Compostela
	0.0351	0.0486	0.0348	0.0444	0.0347	0.0457
	0.0486	0.0351	0.0444	0.0348	0.0457	0.0347
	0.5808	0.4192	0.5607	0.4393	0.5681	0.4319
Rank	1	2	1	2	1	2

3. Results and discussion

In this work, three scenarios on the distribution of importance of the decision-makers' judgments were explored. Results show that these distributions yielded slight changes in the priorities of the warehouse location decision criteria. As shown in Table 4, the priorities yielded the following list:

C1(unit price)≻C4(proximity to the leading supplier)≻C2(transportation cost)≻C5(proximity to customers)≻C17(traffic access)≻C8(accessibility to the road)≻C7(space availability)≻C12(quality and reliability of modes of transportation)≻C16(security of region)≻C6(availability of customers)≻ C22(public facilities condition)

These criteria are identified by obtaining the median of all priorities and choosing those criteria which are above the median. Although small variations exist in the priority values and their corresponding ranks, the order of these criteria is reasonably stable under the three scenarios. This implies that the conditions of engaging more importance to expertise, decision-making power, or none at all have a limited impact on the group decision. A plausible way of explaining such a finding is that the members of the expert group (i.e., the administration team) have a comparable degree of knowledge and expertise on the operations of the warehouse as a distribution centre. With a closely related level of understanding of these operations, the priorities of these criteria would not significantly differ compared to a condition where experts have a more heterogeneous understanding of the domain problem. The ranking of priorities of the criteria indicates that the most crucial (i.e., top five) factors in warehouse location decision-making in the context of a product distribution firm include unit price, proximity to the leading supplier, transportation cost, proximity to customers, and traffic access. These criteria are highly associated with the economic considerations and efficient operations towards downstream and upstream supply chain members. It shows that decision-makers in this industry put more emphasis on maintaining the distribution networks more efficiently at minimum cost. This is consistent with the insights in the current literature. In the Philippines, as in many developing economies, traffic congestion is prevalent (i.e., most notably in the case location), and aiming to minimise the distances and maximise access to suppliers and customers is crucial in enhancing the productivity of the distribution operations. The unit price is associated with capital investment, which is a straightforward consideration in investment decisions. On the other hand, transportation cost is an operational cost, and keeping such a cost plays a huge role in maximising productivity.

With the use of group TOPSIS, the case study revealed that the Talamban site was the best warehouse location under the three different scenarios. This is also consistent with the observation which was obtained in the priorities of the criteria in relation to the distribution of priorities of decision-makers. It supports the previous claim that the expert knowledge and expertise regarding the decision of a warehouse location and the case problem are homogeneous to a considerable extent. It implies that the case firm must establish its warehouse at the identified location. It should be noted that the group decision using TOPSIS is robust on the distribution of expert priorities, as long as their knowledge and expertise are comparable.

Conclusions

The selection of a location for a warehouse requires considering multiple criteria used to evaluate the alternative sites, which is a straightforward implication of real-life decision-making. This set of criteria, often with numerous, contains both objective and subjective factors with non-sharp definitions and limited measurement scales. Furthermore, the presence of multiple decision-makers with different motivations and value systems is prevalent in such a strategic decision-making process. Understanding the impact of these differences in priorities is crucial in a group decision-making environment. In this article, with the use of TOPSIS, a warehouse location decision problem was considered with a significant number of criteria under a group decision-making structure with varying priorities of experts. A case study of a distribution firm was presented to illustrate the approach.

Under three different distribution scenarios of expert priorities (i.e., expertise, decision-making power, and equal weights), results showed that the unit price, proximity to the leading supplier, transportation cost, proximity to customers, and traffic access were considered the most important criteria for selecting a possible site for a warehouse. These findings imply two important insights. First, costs (i.e., investment capital and operational expenses) are important economic considerations in establishing a warehouse and maintaining it, which are inputs to warehouse location decisions. These costs are crucial factors in maintaining the overall profitability. Second, decision-makers put an emphasis on the efficient distribution operations to both downstream and upstream members of the supply chain. These factors, in general, are associated with maximising the productivity of the warehouse operations. Findings also reveal that the varying priorities of the decision-makers have little impact on the group decision, both at identifying priority criteria and the best warehouse location under TOPSIS, which implies that their degree of knowledge and expertise is comparable to a certain extent. This work demonstrates the efficacy of using the TOPSIS in warehouse location decisions under a significant number of criteria, along with an expert group who is tasked with making judgment elicitations. Due to the efficiency and tractability of the required computations, the TOPSIS method provides a useful, practical tool for analysts and decision-makers with limited technical computational expertise in addressing the warehouse location problem.

Nevertheless, this work is not free from limitations. First, the findings in this work, to some extent, are dependent on the case conditions. Thus, these findings may not reflect other cases with different conditions and must be adopted with care. Second, the limited impact of homogeneous knowledge and expertise of experts on the group decision may be anecdotal evidence. A more controlled investigation on such a claim may serve as grounds for future work.

Third, the TOPSIS method works well not only with a considerable number of criteria but also for a significant number of alternatives. Future works may be extended to multiple warehouse location alternatives. Fourth, it is also possible to explore a group decision-making environment where a criterion is evaluated by a decision-maker with a more significant amount of knowledge and expertise. For instance, a criterion for traffic access could be better assessed by a vehicle operator than a CEO. Lastly, other extensions of TOPSIS, such as the use of standard fuzzy sets, hesitant fuzzy sets, type-2 fuzzy sets, neutrosophic sets, and grey theory, under a group decision-making process, could be explored in future work.

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Appendix 1. Comparative analysis of well-known multi-criteria decision-making methodologies (adopted from Özcan et al., 2011)

Characteristics	AHP	TOPSIS	ELECTRE I	ELECTRE II	ELECTRE III
Core process	Creating hierarchal structure and pair-wise comparison matrices	Calculating distance to positive and negative ideal point	Determining concordance and discordance indexes	Determining concordance and discordance indexes	Determining concordance and discordance indexes with indifference and preference thresholds
Necessity to quantify the relative importance of criteria	Yes	Yes	Yes	Yes	Yes
Determining of weights	Pairwise comparison matrices. 1-9 scale	No specific method. Linear or vector normalisation	No specific method. Based on decision maker	No specific method. Based on decision maker	No specific method. Based on the decision maker
Number and type of outranking relations	N*(N-1)/2	1	2	2	1 fuzzy
Consistency check	Provided	None	None	None	Provided
Problem structure	Little number of alternative and criteria or qualitative data	Large number of alternative and criteria, objective and quantitative data	Large number of alternatives and criteria, objective and quantitative data	Large number of alternatives and criteria, objective and quantitative data	Objective and quantitative data, usage of fuzzy logic
Final results	Global, net ordering	Global, net ordering	A kernel	A partial pre-order	A partial pre-order

Appendix 2. Some warehouse location selection criteria

Source	Location selection criteria
Özcan et al. (2011)	unit price; stock holding capacity; average distance to main supplier; average distance to shops; movement flexibility
Dey et al. (2017)	availability of markets; transportation facility; space availability; costs
Demirel et al. (2010)	costs; labour characteristics; infrastructure; markets; macro-environment
García et al. (2014)	accessibility to the area; distance; costs; security of the region; local acceptance of the company; company needs
Alberto (2000)	environmental aspects; costs; quality of living; local incentives; time reliability provided to customers; response flexibility to customers' demands; integration with customers
Chan et al. (2007)	cost expected; traffic access; market opportunity; quality of living; local incentives
Dogan (2012)	quality of labour; quality of suppliers; demographics; geographical location; quality of life; financial efficiency; quality of transportation; government efficiency; quality and infrastructure; regulatory; social and cultural factors; economic performance
MacCarthy and Atthirawong (2003)	Costs; labour characteristics; infrastructure; proximity to suppliers; proximity to markets/customers; proximity to parent company's facilities; proximity to competition; quality of life; legal and regulatory framework; economic factors; government and political factors; social and cultural factors; characteristics of a specific location
Roh et al. (2013)	location; logistics; national stability; cost; cooperation
Melachrinoudis and Min (2000)	cost; traffic access; local incentives
Kuo (2011)	port rate; import/export volume; location resistance; extension transportation convenience; trans-shipment time; one-stop service; information abilities; port and warehouse facilities; port operation system; density of shipping line
Rao et al. (2015)	price of acquiring land; upside delivery flexibility; transportation conditions; service level; human resources condition; environmental protection level; impact on ecological landscape; natural conditions; public facilities condition; security; comply with sustainability laws and regulations; impact on nearby residents; impact on traffic congestion
Colson and Dorigo (2004)	surface of storage; volume of storage; general storage; storage of dangerous items; temperature-controlled storage; separated storage areas; heating; humidity-controlled environment; ventilation-controlled environment; insulated roof and walls; office(s) present on site; distance from nearest motorway; connection to rail; connection to waterways; certified to ISO 9001/9002; certified to SQAS; certified to HACCP; daily opening hours; customs on site; bonded warehouse; feigned warehouse; simple inventory recording; real inventory management; use of bar codes or tags; interfaced computer system; RF communications; (Re-)packaging; order management; transport/distribution; only for receipts and issues; mixed with trans-shipment for third parties; forklift trucks-electric; forklift trucks-gas; forklift trucks-diesel/petrol; tractors for terminal; height stacking; open loading/unloading docks; covered loading/unloading docks; dock levellers; automatic docks; and docks for swap bodies/semi-trailers

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Modelling road traffic safety indices by means of regression with panel data

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ABSTRACT

Although the occurrence of road accidents and the number of road accident casualties in almost all Polish voivodeships has decreased over the last few years, the rate of this change varies considerably from region to region. To provide a better understanding of such a tendency, panel data regression models are proposed to conduct this pilot research which evaluates the relative performance of Polish regions in terms of their road traffic safety. Panel data are multi-dimensional data which involve measurements over time. In the research, a voivodeship is a unit analysed at a group level, whereas a year is a unit analysed at a time level. A two-way error component regression model has been applied to survey the impact of regressors, the group effects, and time effects on a dependent variable. The analysis has been conducted using data acquired from the Statistics Poland Local Data Bank website, as well as from the General Directorate for National Roads and Motorways. The panel data from 16 regions in Poland and the 2012–2018 period have been investigated. The examined models refer to road traffic safety indices defined based on the following characteristics: the number of road accidents, the number road fatalities, and the number of people injured. The results of all the three models indicate a negative effect as regards the GDP per capita, (car) motorisation rate, the indicator of government expenditure for current maintenance of national roads, and the road length per capita. A positive association has been found between the truck motorisation rate and the indicator of local government expenditure on roads. The impact of the region's urbanisation indicators on road safety is ambiguous as, on the one hand, its increase causes a reduction in the road accident and accident injury indices, but, on the other hand, it produces a rise in the accident fatality index. In the models, the significance of time effects has been identified; a decreasing time trend suggests a general improvement in road safety from year to year. Most of the group effects have turned out to be highly significant. However, the effects differ as regards both the road accident and the accident injury indices in magnitude and direction.

KEY WORDS
longitudinal data, road accidents, road accident casualties, fixed effects models

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Introduction

Road accidents and their consequences are a result of failures in the road transportation system. Their output is represented in the form of registered data describing road traffic crashes and their casualties. They are the basis for exploratory data analyses focused on road traffic safety diagnosis and improvement, carried out on a range of granularity levels. The research of aggregated data is somewhat frequently undertaken and commonly concentrated either on

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time series analyses (Dupont et al., 2014) or cross-sectional analyses (Hauer, 2010; Söderlund & Zwi, 1995). The latter is commonly applied to the aggregated data, which have a panel structure (Wachnicka et al., 2018). Panel data, however, provide more information, more variability, less collinearity among the variables, and more degrees of freedom (Baltagi, 2001). Therefore, employing models that consider such a data structure admits an exploration of more issues than cross-sectional or time-series data alone (Kennedy, 2018).

Panel data are also called longitudinal data or cross-sectional time-series data. They have observations on the same organisational units across time. As regards road traffic safety analyses, a year is a period commonly chosen, but the possibilities of cross-section units are extensive, starting, for example, from a set of selected road network sections (small organisational units), then cities to regions, countries (big organisational units) and the like.

In Poland, the occurrence of road accidents and road accident casualties in almost all 16 voivodeships has decreased over the past few years, which is illustrated in Fig. 1. The figure presents the time series of the total number of road traffic accidents and the total number of accident fatalities. Each voivodeship is given an identifier as follows (CS stands for Cross Section): CS1 — Dolnośląskie, CS2 — Kujawsko-Pomorskie, CS3 — Lubelskie, CS4 — Lubuskie, CS5 — Łódzkie, CS6 — Małopolskie, CS7 — Opolskie, CS8 — Podkarpackie, CS9 — Podlaskie, CS10 — Pomorskie, CS11 — Śląskie, CS12 — Świętokrzyskie, CS13 — Warmińsko-Mazurskie, CS14 — Wielkopolskie, CS15 — Zachodniopomorskie, CS16 — Mazowieckie. The last identifier has intentionally been attributed to the largest voivodeship, both in terms of area and population, thus making it the reference category at the further modelling stage.

Like in other countries, in Poland, numbers of road traffic accidents, accident fatalities and injuries are the main fundamentals of road safety measures at a macro-level analysis. According to Fig. 1, a general trend of these measures is descending for the whole country. However, the patterns of change vary considerably from region to region. Certain disturbances can be observed for some regions, such as the Wielkopolskie Voivodeship (CS14) where a rapid (by 34.8%) growth of the number of accidents occurred in 2017. There is also a discrepancy between the road accident fatalities for the Mazowieckie Voivodeship (CS16) and the remaining regions (its large population and wealth can partly account for this). Thus, considering the character of the aggregated information delivered for each region within a certain period, it is justified to estimate a panel data model. These types of models enable the description of the influence of time and unit variations as well as exogenous factors on the endogenous variables, i.e., measures of road safety.

The objective of the research is to address the following issues:

- possible existing differences in the levels of road safety among individual regions of Poland;
- possible changes in safety levels with time and the nature of these changes;
- presumable relationship between selected factors, particularly road expenditure, characterising Polish regions, and the level of road traffic safety.

The contribution of the work is that:

- endogenous variables are the measures of road safety calculated in relation to road length and not to population because road length is a more stable characteristic for a voivodeship than the number of inhabitants;

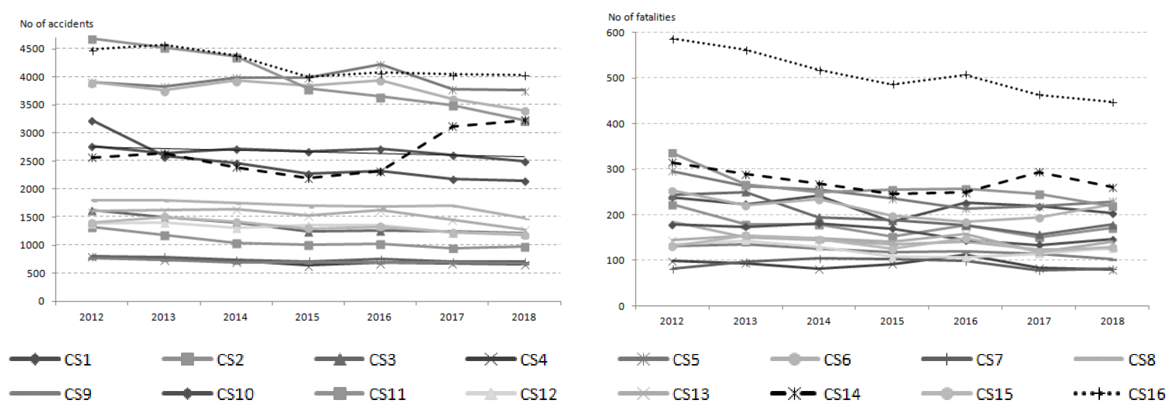

Fig. 1. The dynamics of road traffic accidents (left) and the accident fatalities (right) per voivodeship in Poland in 2012–2018
Source: authors' own elaboration

- unlike in other research, motorisation rates by motor vehicle type are analysed, considering cars, trucks, and motorcycles;
- expenditure on roads is investigated, in particular including structural expenditure on national roads.

The study is divided into several sections. Following the Introduction, there is a literature review of how panel data models are applied in the road traffic safety investigation. Then, the empirical model is explained. The next part of the work presents the data to be analysed and a set of potential explanatory variables along with explained variables, which are certain measures indicating the level of road traffic safety. Then, the results and the corresponding discussion are provided regarding full and backward selection regression models. Finally, the main conclusions are presented.

1. Literature review

Extensive research has been carried out in the field of road accidents, and it has been done in different ways. The synthesis of various approaches developed in the road safety analyses, their principles, and the characteristics of developed estimation techniques are discussed for example by Laaraj and Jawab (2018), Muthusamy et al. (2015), Antoniou et al. (2016), Badura (2017) and other authors indicated in the list of references of this article. This study reviewed the selected literature covering different issues related to road safety analysis with the application of panel data models.

Numerous studies have been devoted to analysing road traffic safety based on aggregate data (Besharati, 2020). However, there are limited sources available, in which researchers make use of the attractiveness of the panel data structure. Yet, in this respect, a variety of possibilities are considered regarding the explained variables that characterise a cross-section unit in a time unit, such as the Gross Domestic Product (GDP) per capita, population density, health care issues, motorisation rate, and road infrastructure. The number of road accidents or the number of road accident casualties (sometimes in relation to population) are road safety measures estimated as output variables. Different types of panel data models are employed, with the number of cross-section (organisation) units N and the number of time units T adapted to the needs of research.

Fixed effect panel data models with annual dummies (to capture the common trend in all the provinces) were estimated independently for urban roads in total within a province and urban roads within the capitals of the provinces in the study by Castro-Nuño et al. (2018). A total number of urban road traffic accidents and a number of urban road traffic accident fatalities per accident were modelled using the N = 50 Spanish provinces and T = 11-year time units (2003–2013) data structure. The general conclusion was that in the case of cities in Spanish provinces, a wider urban spread inevitably led to more severe traffic accidents, whereas road fatality was lower in urban areas with denser populations (thus, more densely concentrated).

Annual death counts and road accident injuries were investigated with the use of one-way fixed-effect models, with time trend considered, for the road network as well as for the interurban part of the network in Spain (Albalate, 2013). In this respect, the panel with N = 50 Spanish provinces and T = 21-year time units (1990–2010) was employed. The impact on road safety was evaluated in relation to selected characteristics of Spanish provinces and, in particular, to recent road infrastructure spending together with the main regulatory changes introduced. The results demonstrate that both regulations and road infrastructure spending influence road safety. In particular, road maintenance expenses produce a significant safety benefit in terms of reducing road accident fatalities and injuries.

The number of road traffic accidents and the number of road traffic accident casualties (injuries and fatalities) were the output variables in two-way fixed effect panel data models estimated for N = 846 road control stations of the Spanish highway network and T = 5-year time units (2008–2012) to explore the role of Public Private Partnerships (PPP) along with road infrastructure and demographic characteristics (Albalate et al., 2019). The quality of road design was indicated as the most relevant aspect influencing road safety outcomes. Nevertheless, evidence was found suggesting that privately operated highways were positively correlated with better road safety outcomes for roads of similar quality.

The number of fatalities per 100 000 population (as a measure of safety) was estimated in two-way fixed effect panel data models for N = 30 provinces in Iran and T = 11-year time units (2005–2015) (Besharati et al., 2020). The results revealed that the fatality rates were positively associated with certain exposure proxies, but negatively related to the variables representing the level of urbanisation. The increase in the number of speed cameras turned out to be connected with the reduction of fatality rates. The differences between the Iranian provinces as well as the time decreasing trends were identified with respect to the discussed road safety output.

In the study where the cross-sectional units had a greater level of granularity, a variety of panel data models were investigated after taking a natural logarithm of all variables in the model (Yaseen, 2018); the causality of road traffic fatalities per million people was investigated in the panel of 30 OECD countries and T = 21-time units (1995–2015). The long-run regression results indicated a significant role of health expenditure, trade openness, and research and development engagement in the reduction of road traffic fatalities.

Kweon and Kockelman (2005) analysed how speed limit changes on high-speed roadways affected total safety. They defined the panel consisting of T = 4-years and over 63 000 homogenous road segments. Interestingly, results indicated that speed limit changes did not influence fatal crash rates. Fatal and non-fatal crash rates decreased for road design elements, such as wider shoulders and more gradual curves. However, when traffic levels rose, non-fatal rates remained constant but fatal rates decreased.

Annual data for 1997–2013 of 51 US states were analysed by Ahangari, Atkinson-Palombo, and Garrick (2017). The results of their research showed that vehicle miles travelled, vehicles per capita, and infant mortality rates (as a proxy of health care quality) have the strongest positive impact on traffic fatality rates. The authors also found that the states with a higher urban density and more walking were associated with lower traffic fatality rates. Some suggestions were made regarding the use of multimodal transportation for the reduction of fatality rates.

2. Research methods

Panel data combine the characteristics of cross-sectional data and time series; they contain information about N objects (groups, units, spatial elements) registered in T time units for each object. The data set defined in this way consists of N · T observations. Panel data prove better at identifying and measuring effects that are simply not detectable in pure cross-section or pure time-series data (Baltagi, 2005). Panel regression models are derived from the multiple linear regression model of the form:

$$y_{it} = \alpha + \sum_{k=1}^{K} \beta_k x_{kit} + \varepsilon_{it} \tag{1}$$

and they have the generalised form, in which the above model (1) is a two-way model, in which the random component ε_{it} is decomposed into three components: unit (μ_i) and time (θ_t) effects account for both unit-specific (but time-invariant) and time-specific (but unit-invariant) and the purely random component v_{it}:

$$y_{it} = \alpha + \sum_{k=1}^{K} \beta_k x_{kit} + \mu_i + \theta_t + v_{it} \tag{2}$$

The meaning of the symbols in equation (2) is as follows:

- i, t indices denoting the object (subject, group, unit, section element) $i = 1, \ldots, N$, and time period $t = 1, \ldots T$, respectively;
- α, β structural parameters (constant coefficients) as in the classic multiple linear regression model, the β vector (vector of slopes) determines the effect of the exogenous variables X_k on the endogenous variable Y;
- x_{kit} the k-th explanatory variable;
- K the number of exogenous variables;
- μ_i individual effect resulting from the observation belonging to the i-th group also referred to as group effect;
- θ_t time-specific effect;
- v_{it} the random component of the model, $v_{it} \sim IID(0, \sigma_v^2)$.

The panel data model assumes that all coefficients are constant. Group effects μ_i reflect the individual characteristics of units that are constant over time for a particular entity (they are not subject to change over time). Time effects θ_t remain constant for all objects at a given time. The presence of effects of both types (group and time) in the regression equation (2) defines a two-way panel data model, while the presence of only one type of effects defines a one-way panel data model. In each of these cases, they can also be random-effects or fixed-effects models.

In the fixed-effects model, the differences between objects and periods are expressed by assigning this information to a component specific to the object or to a period, which is incorporated in the equation by coding — creating zero-one variables for a group or time (dummy variables). The differences between group and time units are captured by the intercepts in the model, which means that each dummy variable (except the reference one) is described by its specific constant. The correlation between individual errors and exogenous variables is allowed (Park, 2011).

The estimated panel data model requires verification which will confirm its accuracy and suitability. The first commonly used tool is the F test; rejecting the null hypothesis implies that the combined influence of individual effects on the endogenous variable is significant.

When applying the Breusch–Pagan test, it can be verified whether the variance of the individual effects component (group or time) is zero; rejection of the null hypothesis allows to conclude that the model with specified group or time effects is better than the model in which these effects have not been specified. In turn, in the Hausman test, rejection of the null hypothesis means the possibility of a correlation between exogenous variables and random effects, which implies the legitimacy of building a fixed-effects model. Then, the LSDV (Least Squares Dummy Variables) method is used to estimate this type of model.

In the study Excel and GRETL computer programs were used to pre-process data and conduct all the calculations.

3. Data description

In the proposed panel data models, a voivodeship (region) is the entity (organisation) unit and a year is the time unit, to which all the variables refer. There are 16 regions in Poland and the analysed period covers 2012–2018. No data are missing as all entities have measurements in the whole period. The same entities are observed for each period. Thus, a well-organised balanced fixed panel data set (Park, 2011) is subject to the analysis. It consists of 112 records ($N \cdot T = 16 \cdot 7$). The majority of data were acquired from the Statistics Poland Local Data Bank (SPLDB) website (https://bdl.stat.gov.pl/BDL/dane/podgrup/temat, 19-22.02.2020). However, some specific information on expenditure on national roads was kindly provided by the General Directorate for National Roads and Motorways, Poland, at the request of the authors.

A variety of indices are used to measure road traffic safety. The level of fatality is commonly represented as the number of fatalities per 100 000 people (IRTAD, 2014), but it has some limitations in highly populated and poorly motorised regions. Another indicator is fatalities per distance travelled. Yet, this is not always easily available. Instead, fatalities per 10 000 registered vehicles are utilised, which, though, may be misleading when traffic levels are different (IRTAD, 2009).

Considering the multi-faceted approach to the phenomenon under study, certain indicators have been proposed as measures for the level of road traffic safety. They are relative measures defined as the endogenous (output) variables, arising from the concept of a variety of measures used in the comparison of traffic accident data between countries or between regions (Farchi et al., 2006):

- RA100KM — Road Accidents calculated as the number of road traffic accidents per 100 road kilometres. Data source: SPLDB;
- RAFR100KM — Road Accident Fatalities calculated as the number of deaths due to road traffic accidents (according to the Vienna Convention's international criterion) per 100 road kilometres. Data source: SPLDB;
- RAI100KM — Road Accident Injury calculated as the number of injuries due to road traffic accidents per 100 road kilometres. Data source: SPLDB.

Despite the fact that demographic indicators are commonly used in the literature, which means that a threat variable (such as the number of accidents, fatalities, or injuries) is related to the fixed number of human population unit, another approach is adopted in this work.

A fixed road length unit has been proposed as the reference, which is connected with the fact that the variability of this reference is smaller than that of the population reference. This is particularly important when data have a panel structure.

Selected characteristics on demography, economy, and road infrastructure were considered as exogenous (input) variables used to diagnose their influence on the road traffic safety expressed by measures calculated from the data on road traffic accidents and their severity.

Variables were selected characterising sources that may influence existing road safety conditions: socio-economic features, road-traffic conditions, expenditure on national roads made by the General Directorate for National Roads and Motorways and by the local governments.

The first group of variables characterises the socio-economic growth of the region; they can be considered as a stimulus for the growth of motorisation, road traffic and exposure.

- GDPPC — Gross Domestic Product Per Capita (in PLN) is the broadest quantitative measure of a nation's total economic activity. It represents the monetary value of all goods and services produced within specific geographic boundaries over a given period. Data source: SPLDB.
- RUI — Region Urbanisation Indicator is the number of people that live in urban areas in relation to the total number of the region inhabitants. In Poland, an urban area is a locality that has been granted a city charter. The level of urbanisation influences the magnitude of traffic generation effects. Data source: SPLDB.

Another category of variables refers to a region's motorisation indicators, defined using the number of motorised vehicles for the region. Vehicle type was taken into account as this attribute is strongly connected with road traffic safety.

- CMR — Car Motorisation Rate is the number of passenger cars per 1 000 inhabitants. Data source: SPLDB.
- TMR — Truck Motorisation Rate is the number of trucks (light, medium, and heavy) per 1 000 inhabitants. Data source: SPLDB.
- MMR — Motorcycle Motorisation Rate is the number of motorcycles per 1 000 inhabitants. Data source: SPLDB.

The remaining input variables relate to road infrastructure, which is one of the most important road safety components. A well-developed and modern road network, with the appropriate density of highways, expressways and express roads, is a precondition for a properly functioning national economy. Thus, in Poland, the intensive modernisation and new road investments have significantly accelerated, especially since the accession to the EU. The scope of these activities and amounts spent depend on the classification of Polish roads. According to relevant law regulations, there are four public road categories (https://www.lexlege.pl, 11.04.2020): national, voivodeship, county and communal, as presented in Table 1, where information is ordered from the highest to the lowest road category. Each road category is determined by technical conditions and operational requirements; all highways and expressways are national roads in Poland. The road owner covers all expenses related to construction, road network maintenance and repairs. However, based on mutual agreements and cooperation, funds may be transferred to cover expenses for roads of other categories. A competent road manager is responsible for the implementation of the tasks related to these direct road expenses.

The following exogenous variables were used to describe the Polish road infrastructure in the analysis.

- DCR — Dual Carriageway Ratio is the percentage of the length of two-way roads in the total length of public roads. Such roads are designed to meet higher standards than one-way roads, separated by a central reservation for traffic travelling in opposite directions. Dual carriageways (among other benefits) improve road traffic safety over single carriageways. Data source: SPLDB.
- RLPC — Road Length Per Capita is the indicator of the length of public roads in kilometres to the number of voivodeship inhabitants.
- SGTERK — Self-Government Total Expenditure per Road Kilometre (per one kilometre of public roads), in thousands of PLN. The variable represents the total expenditure of voivodeships, and counties and communes (belonging to the voivodeships) per one kilometre of public roads (national, voivodeship, county, and communal). Data source: SPLDB.

In the analysed period (2012–2018), the national roads accounted for only about 7% of the public road network. However, they carry more than 60% of total

Tab. 1. Characteristics of Polish public road categories

Road category	Road class	Road owner	Road manager (administrator)
National roads	Motorway, expressway, main road of accelerated traffic	The Treasury	General Director of National Roads and Motorways, Concessionaire
Voivodeship roads	Main road of accelerated traffic, main road	Voivodeship self-government	Voivodeship Board
County roads	Main road of accelerated traffic, main road, collector road	County self-government	County Board
Communal roads	Main road of accelerated traffic, main road, collector road, local road, local access road	Communal self-government	Head of the Commune (Mayor, Mayor of the City)

Source: authors' own elaboration

traffic, there were 24.5%–28% of the total number of accidents recorded on these roads, which resulted in as many as 36%–39% of the total number of road accident fatalities. Raising road standards, especially as regards the national roads network, is said to improve the situation. Therefore, the information concerning major and current expenditure on national roads made by the General Directorate for National Roads and Motorways (GDNRM or GD) has been considered. The following variables were included in the analysis to evaluate how the outlays for the most important category roads were effective in terms of general road traffic safety.

- GDICERK — General Directorate Investment Construction Expenditure per one kilometre of national roads, in thousands of PLN. Data source: GDNRM.
- GDRRERK — General Directorate expenditure on Road network Repairs per one kilometre of national roads, in thousands of PLN. Data source: GDNRM.
- GDCRMERK — General Directorate expenditure on Current Road network Maintenance per one kilometre of national roads, in thousands of PLN. Data source: GDNRM.

4. Modelling results

In the modelling procedures, the last category of the cross-section and time unit variables is the reference. This means that the Mazowieckie Voivodeship is the reference for cross-section, as is the year 2018 for time. The robust standard errors technique was employed to obtain unbiased standard errors of OLS coefficients under heteroscedasticity. Table 2 presents the outcome of the modelling. The endogenous variable names were used to identify related models further on in the study.

The first part of Table 2 contains the results of consecutive stages of research leading to the final forms of the models. Using the F test, the hypothesis of individual effects was verified. The p-values for individual models indicate the rejection of the null hypothesis, which implies the validity of using the panel data model for each considered endogenous variable. The results of Breusch–Pagan and Hausman tests justify the choice of fixed-effects models.

For each endogenous variable, two separate models were constructed: the full model, which includes all the proposed exogenous variables, and the re-estimated model with variables obtained in the backward selection procedure, in which the significance level for entering a variable into the model was set to 10%. As can be seen, the sign and magnitude of all the variables significant in the backward selection models are consistent with those of the respective full models, indicating generally stable results.

For each model, the elimination of insignificant variables increased the adjusted R^2 value, thus confirming the validity of the model final form obtained in the backward selection procedure.

Adjusted R^2 exceeding 95% and the graphic illustration of predicted and observed values in Fig. 2a and 2c, respectively, indicate that models for RA100KM and RAI100KM variables are high-quality models. A slightly worse fit (adjusted R^2 does not exceed 80%) was obtained in the case of the RAF100 variable, which is due to the relatively high variability of the feature within individual voivodeships (Fig. 2b).

The differences in the values of the analysed endogenous variables by voivodeships are presented in the form of box plots in Fig. 3. Relating them to the obtained results, it may be concluded that, in principle, the structure of mutual relationships identified in the models reflects the patterns illustrated in the plots.

5. Discussion of the results

The discussion of estimation results presented below refers to the final models.

GDPPC — a standard measure of economic well-being was found to be statistically significant in the case of the RAF100KM model but insignificant for the RA100KM and RAI100KM models. At the same time, the CMR variable turned out to be significant for the last two models discussed but insignificant for the first one. What is more, the direction of the effects' influence is the same, and the magnitude of their influence is remarkably similar. It can be assumed that both exogenous variables under consideration are a proxy of voivodeship economic development and growth (thus being also correlated). The findings confirm that better economic conditions of regions are associated with lower rates of accidents, fatalities as well as injuries.

Road traffic with a high proportion of trucks may imply heightened hazard as regards road traffic safety. All the models estimated in the study confirm this relationship; both the road accident number and the road accident casualty number (fatalities and injuries)

Tab. 2. Estimation results of the panel data models for the three road traffic safety measures (endogenous variables)

Model name	**RA100KM**		**RAF100KM**		**RAI100KM**	
F test DF(15,85)	F = 49.55 (p-value = 0.00)		F = 5.91 (p-value = 0.00)		F = 43.04 (p-value = 0.00)	
B-P test	Asymptotic Chi-2 = 161.05 (p-value = 0.00)		Asymptotic Chi-2 = 19.56 (p-value = 0.00)		Asymptotic Chi-2 = 134.94 (p-value = 0.00)	
Hausman test	Asymptotic Chi-2 = 47.25 (p-value = 0.00)		Asymptotic Chi-2 = 39.61 (p-value = 0.00)		Asymptotic Chi-2 = 61.85 (p-value = 0.00)	
Panel data model estimation results						
Model type	**Full***	**Backward selection**	**Full***	**Backward selection**	**Full***	**Backward selection**
Exogenous variable	Estimator (p value)	Estimator (p value)	Estimator (p value)	Estimator (p value)	Estimator (p value)	Estimator (p value)
Intercept	3.89 (0.74)	4.28 (0.00)	0.1 (0.95)	0.49 (0.00)	6.54 (0.76)	16.94 (0.00)
GDPPC	-0.05 (0.32)		-0.01 (0.43)	-0.01 (0.01)	-0.05 (0.36)	
RUI	-19.97 (0.16)	-14.90 (0.00)	1.51 (0.59)	1.04 (0.00)	-27.46 (0.28)	-14.45 (0.00)
CMR	-0.01 (0.32)	-0.01 (0.05)	0 (0.59)		-0.02 (0.45)	-0.04 (0.00)
TMR	0.20 (0.00)	0.11 (0.00)	0.01 (0.38)	0.005 (0.00)	0.26 (0.04)	0.20 (0.00)
MMR	0.01 (0.97)		0.02 (0.39)	0.01 (0.00)	-0.03 (0.84)	
DCR	-0.22 (0.66)		-0.02 (0.79)		-0.65 (0.25)	
RLPC	136.40 (0.49)		-47.93 (0.05)	-53.82 (0.00)	296.18 (0.36)	
SGTERK	0.03 (0.01)	0.02 (0.00)	0 (0.47)		0.03 (0.00)	0.03 (0.00)
GDICERK	0 (0.65)		0 (0.35)	0.00004 (0.02)	0 (0.09)	
GDRRERK	0 (0.88)		0 (0.89)		0 (0.66)	
GDCRMERK	0 (0.71)		0 (0.26)	-0.002 (0.02)	-0.01 (0.67)	
CS1	6.51 (0.00)	4.63 (0.00)	-0.11 (0.62)	-0.19 (0.00)	9.64 (0.01)	6.80 (0.00)
CS2	0.03 (0.99)		-0.24 (0.40)	-0.28 (0.00)	0.50 (0.88)	
CS3	-3.22 (0.36)	-1.73 (0.00)	0.08 (0.88)		-4.38 (0.37)	-1.81 (0.00)
CS4	1.44 (0.52)	1.41 (0.00)	-0.26 (0.25)	-0.31 (0.00)	3.32 (0.31)	3.02 (0.00)
CS5	5.82 (0.00)	5.14 (0.00)	-0.15 (0.35)	-0.20 (0.00)	8.14 (0.00)	7.46 (0.00)
CS6	2.54 (0.35)	2.83 (0.00)	-0.07 (0.88)	-0.19 (0.00)	3.35 (0.40)	3.41 (0.00)
CS7	1.35 (0.63)	1.09 (0.00)	0.18 (0.68)		2.00 (0.66)	3.65 (0.00)
CS8	-0.70 (0.88)		-0.22 (0.76)	-0.30 (0.00)	-0.06 (0.99)	
CS9	-0.94 (0.71)		0.01 (0.98)		-1.60 (0.66)	-1.61 (0.00)
CS10	7.72 (0.00)	6.96 (0.00)	-0.25 (0.13)	-0.34 (0.00)	10.92 (0.00)	8.86 (0.00)
CS11	12.33 (0.00)	9.19 (0.00)	-0.35 (0.38)	-0.42 (0.00)	17.02 (0.01)	11.09 (0.00)
CS12	-6.48 (0.06)	-2.74 (0.00)	0.05 (0.93)		-9.03 (0.09)	-4.66 (0.00)
CS13	3.33 (0.20)	3.45 (0.00)	-0.07 (0.80)	-0.11 (0.00)	4.57 (0.19)	3.58 (0.00)
CS14	-2.01 (0.38)	-1.05 (0.00)	-0.19 (0.60)	-0.25 (0.00)	-2.19 (0.50)	
CS15	3.52 (0.10)	3.09 (0.00)	-0.35 (0.17)	-0.35 (0.00)	5.10 (0.14)	2.89 (0.00)
Year 2012	2.80 (0.15)	2.71 (0.00)	0.15 (0.48)	0.16 (0.00)	3.25 (0.34)	0.51 (0.02)
Year 2013	2.29 (0.18)	2.25 (0.00)	0.13 (0.53)	0.13 (0.00)	2.59 (0.38)	0.34 (0.01)
Year 2014	1.72 (0.25)	1.75 (0.00)	0.11 (0.55)	0.11 (0.00)	1.83 (0.48)	
Year 2015	1.32 (0.25)	1.34 (0.00)	0.04 (0.77)	0.05 (0.03)	1.39 (0.48)	
Year 2016	1.33 (0.09)	1.36 (0.00)	0.04 (0.73)	0.04 (0.05)	1.59 (0.23)	0.65 (0.00)
Year 2017	0.73 (0.10)	0.71 (0.00)	-0.01 (0.84)		0.95 (0.19)	0.40 (0.00)
Adjusted R^2	0.9740	0.9744	0.7759	0.7960	0.9727	0.9732
AIC	133.633	124.946	−329.891	−346.322	194.218	184.226

* The 10% significant effects for full models are marked by a grey background.

Source: authors' own elaboration

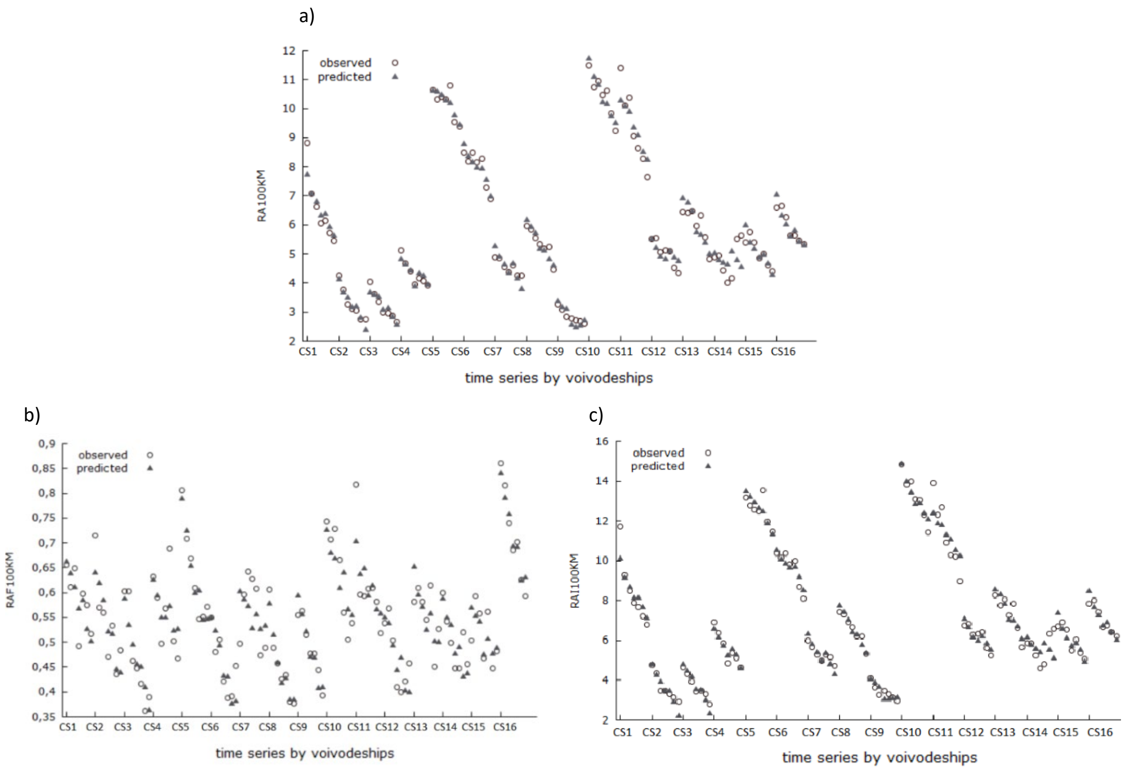

Fig.2. Illustration of the goodness of fit for the panel data models for the variables: RA100 (a), RAF100 (b), RAI100 (c)
Source: authors' own elaboration

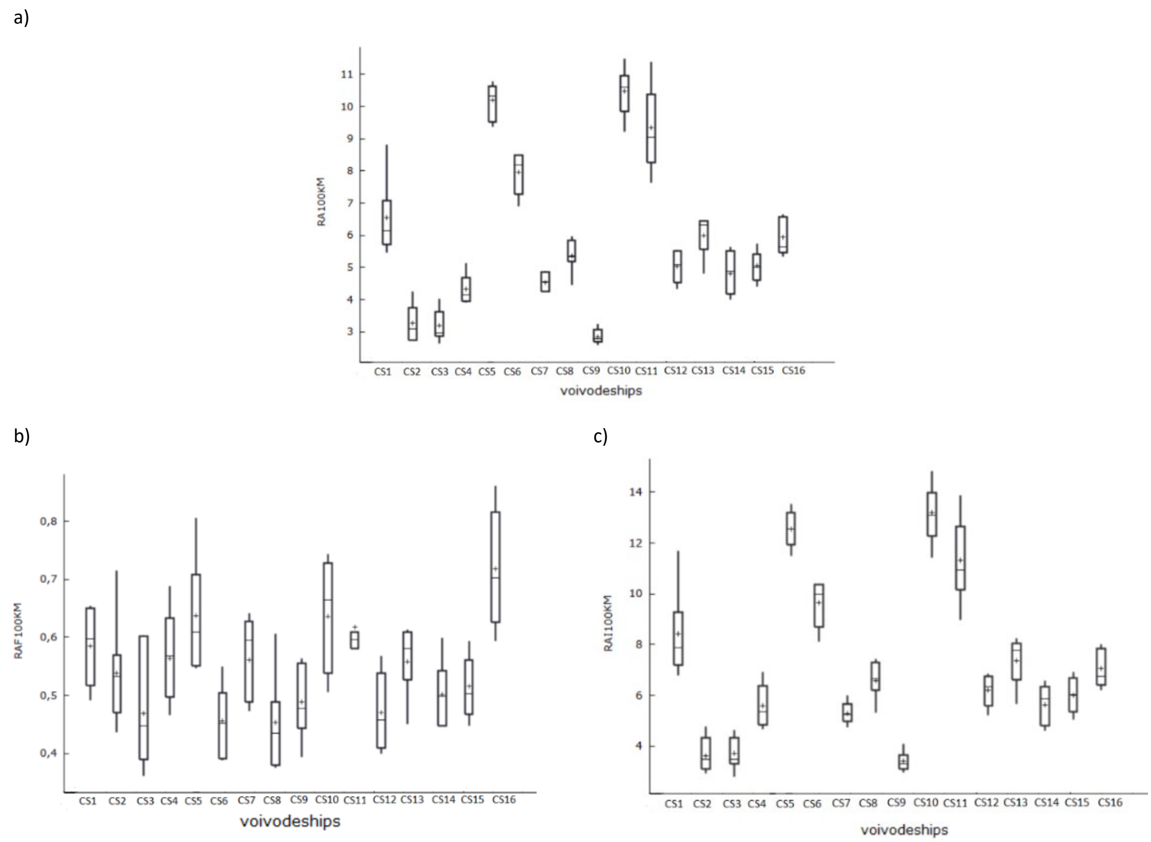

Fig. 3. Illustration of the goodness of fit for the panel data models for the variables: RA100 (a), RAF100 (b), RAI100 (c)
Source: authors' own elaboration

increase along with the TMR value (increase). The last indicator of motorisation rate MMR proved to be significant and positively associated with the fatality rate in the RAF100KM model. This is consistent with the fact that motorcyclists, who are vulnerable road users, are highly likely to be fatal accident casualties. Rising motorisation rates for trucks and motorcycles lead to increased traffic fatalities while rising motorisation rate for cars does not.

The urbanisation indicator (RUI) is inversely related to the accident rate and injury rate while positively related to the increase in the fatality rate. The higher the urbanisation rate, the smaller the number of accidents and injuries per road kilometre, but the higher the number of fatalities (thus, more serious consequences). On the one hand, the differences may result from the fact that a much larger percentage of unprotected road users prone to exposure (pedestrians, cyclists) occur in cities (accidents involving such participants reach up to ¼ of the total number of accidents). On the other hand, the relationship between RUI and RA100KM and RAI100KM may become reverse, which may be connected with the progressive improvement of rural road infrastructure. The results seem to be surprising; therefore, further research is necessary.

The DCR variable turned out not to be significant in any of the models. Still, its role as a specific measure of road infrastructure development, which is an essential element of the overall development of the region, is represented in the models by the GDPPC or CMR variables.

The indicator of the length of public roads to the number of voivodeship inhabitants (RLPC) affects accident fatality rates in the RAF100KM model, but in the remaining models, it turns out to be insignificant. Extending the roadway network can be associated with the improvement of road quality as a consequence of the investment or modernisation processes. This aspect of increasing the length of roads and relating it to the population density can account for the decline in road hazard, expressed in the reduction of the number of fatalities. Yet, the result should be interpreted carefully since other factors, featuring the heterogeneity of the RLPC variable, such as intersection density or the impact of the road classification (national, voivodeship, etc.), were not included in the model.

Road expenditures investigated in the study work on distinct levels. Local authorities finance regional (voivodeship, county and commune) roads and cover some of the costs directly related to national roads. These total amounts are provided by the SGTERK variable. However, in the case of national (major) roads, expenses have been differentiated according to their structure by considering such variables as GDICERK, GDRRERK and GDCRMERK. While it is presumed that an increase in road expenditure improves road safety outcomes, the obtained results fail to confirm this. Such a result may be due to several factors, such as not considering the time delay of SGTERK, GDICERK, GDRRERK variables (the expected effect of the investment requires time) and the fact that the structure of expenditure of local administrations has been left out of consideration. Only in the RAF100KM model, the GDCRMERK variable is statistically significant, and has a negative effect on the endogenous variable. The increasing expenditure on the current maintenance of national roads immediately translates into a reduction in the number of fatalities on these roads (this was also reflected in the overall picture of road network safety).

Individual intercepts are included to identify individual-specific group and time characteristics. These intercepts are called fixed effects.

The specification of the two-way panel data model made it possible to confirm the correctness of the inclusion of time effects in the research. The significance of these effects in the models RA100KM, RAF100KM, RAI100KM along with the identified, decreasing time trend suggest that new advances in vehicle technology, national transportation safety policies, educational initiatives, rising public awareness, and other dedicated activities have changed over time, with safety generally improving year to year.

Also, most of the cross-sectional effects are highly significant; in the total number of 15 dummy variables, 12 appeared in the RA100KM and RAI100KM backward models and 11 in the RAF100KM backward model. This means that region specificity factors (such as: geographical conditions, road user features, business-oriented activity, educational and environmental aspects, and also administrative policies) not included in the models, might significantly affect the differences between voivodeships in the considered measures of the level of road traffic safety. However, the significance is not uniform. There are eight cross-sections (CS1, CS4, CS5, CS6, CS10, CS11, CS13, CS15) evidently distinguished from the reference cross-section (Mazowieckie) by the three rates: accident, fatality, and injury. These effects are positive in both RA100KM and RAI100KM models, but not of similar magnitude. Only for three voivodeships (Lubelskie — CS3, Świętokrzyskie — CS12, and Wielkopolskie — CS14) smaller values of RA100KM were identified; these regions are also characterised by smaller values of the RAI100KM indicator or its lack of significance. In relation to all the region effects included in the RA100KM and RAI100KM models, the Śląskie Voivodeship (CS11) performs worst (relatively large positive influence) while the Świętokrzyskie Voivodeship (CS12) performs best (relatively large negative influence). Although the above results may arise from the specifics of the voivodeships, completely different factors may define these specifics (historical, economic and social conditions). The RAF100KM results show that the Mazowieckie Voivodeship is doing worse than 11 Polish regions in terms of accident fatality rate (statistically significant negative values for respective cross-section parameters). This somewhat surprising outcome might be a consequence of the fact that both the Region Capital City of Warsaw and the Mazowieckie Voivodeship have been treated as one.

Conclusions

The objective of the research was to investigate the relative road safety performance of the Polish voivodeships, with a special focus on expenditures on roads. The study set out to identify factors significantly affecting the measures of the road safety level expressed in terms of accident rate as well as fatality and injury rates. The two-way panel data models with fixed effects were built for the annual data from 2012 to 2018 and for 16 Polish regions.

The panel model results suggest a varied impact of motorisation rates in terms of trucks and passenger cars on road safety. Motorcycles have proved to be positively relevant only to fatality rate. It has been found that the effect related to greater exposure to accident rate and injury rate is stronger for trucks than for passenger cars.

Self-government total road expenditure turned out to be significantly and positively associated with road accident rate and injury rate, while the increase of national road maintenance expenditure significantly contributed to a reduction in the road fatality rate. These promising results require a more in-depth analysis.

It has been detected that there were unquestionable differences among voivodeships taking into account the studied endogenous variables. That considerable variation in road safety could be the key factor in planning road investments and other dedicated activities, in particular, intensified police patrols. It is optimistic that in most voivodeships, the values of the examined road safety measures decreased over the considered period.

Panel data models are extremely helpful in analysing various questions related to road traffic safety policy in different regions. In particular, such models could be used in identifying fund allocation based on the relative risk exposure of the regions.

The results obtained for the road accident rate and the road accident injury rate were very similar, which suggests that the indicators related to the number of road injuries and the number of road fatalities are sufficient for modelling road safety, obviating the need to create models for the number of accidents.

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Forecasting operational costs of technical objects based on the example of railbuses

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ABSTRACT
The purpose of the article is to present the method for forecasting one of the three categories of exploitation costs, i.e., operational costs. The article analyses the available subject literature discussing the methods of measuring operational costs used in the LCC analysis. The presented method for forecasting operational costs of technical objects applies econometric modelling, probability distributions and certain elements of descriptive and mathematical statistics. The statistical data analysis was performed using the functions and commands available in Microsoft Excel. Weibull++ application was also used for constructing probability distributions for random variables and verifying hypotheses. The method was tested on eight single-mode railbuses, operated by one of the regional railway companies providing passenger transport. An ex-post relative forecast error was used to measure the level of accuracy of the operational cost forecast. The analysis of the compliance between forecasted cost value and the actual costs showed extensive convergence as evidenced by the level of estimated relative errors. In forecasting the operational costs of railbuses, the average error was approx. 2.9%. The presented method can, therefore, constitute the basis for the estimation of both operational costs and exploitation costs, which represent an important cost component considered when assessing the profitability of purchasing one of the several competing technical objects offered by the industry.

KEY WORDS
forecasting, operational costs, analysis of the life-cycle cost (LCC)

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Introduction

Operational costs of a technical object[1], i.e., the costs incurred in the course of operation (use) of an object, represent one of the three categories of exploitation costs (service life costs). In addition to operational costs, exploitation costs of an object cover (Adamkiewicz, 1983; Dietrich et al., 1999; PN-EN 60300-3-3, 2001):

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[1] The term technical object (exploitation object) refers to products serving as a tool for transforming (moving or processing) matter, energy or information. This term is usually used to describe machines, devices and means of transport.

- damage costs including, e.g., costs of restoring the object's serviceability (in other words repair costs, corrective maintenance costs), penalties resulting from the object's unavailability for operation and the loss of revenues caused by the unplanned interruption of operation;
- preventive maintenance costs, which include the costs of performing preventive maintenance services (inspections and the related repairs) and also, if necessary, the loss of revenues resulting from the planned interruption of operation.

The exploitation costs of a technical object, along with the costs of its acquisition and decommissioning, represent life-cycle costs (Legutko, 2004; PN-EN 60300-3-3, 2001; Woropay, 1996). Experience shows that exploitation costs are 2 to 20 times higher than the acquisition costs of the object (Kowalski et al., 2007; Ryan, 1968). Therefore, the exploitation costs should remain the primary subject of analysis while performing a comparative assessment of the alternative purchase solutions.

The article addresses the role of operational costs in the analysis of life-cycle cost (LCC). It discusses methods for estimating operational costs of technical objects, most commonly used in practice and suggested in the subject literature. Also, it presents a method for forecasting the operational costs of a technical object. Single-mode railbuses operated by one of the regional railway companies providing passenger transport were chosen as the research object. The method was tested to verify its practical applicability when estimating the operational costs of an object.

1. Literature review

The conducted analysis of the available publications, discussing the LCC analysis, shows that:

- the basic components of operational costs cover the costs of energy consumption (e.g., fuel, diesel) and also the labour costs of employees using the object;
- the basic parameters2 of operational costs include the costs of human labour per unit of time, the number of people using the technical object, the purchase price of an energy unit and energy consumption per time unit;
- the average unit parameter values resulting from the analysis of previous years are adopted in the calculation of operational costs;
- operational costs depend on the value of the technical object readiness index;
- operational costs are calculated on an annual basis and next multiplied by the number of years of the object operation or for the entire life cycle of the technical object;
- the operational costs of a technical object are estimated based on constant prices or a discount coefficient, which considers the fluctuations of money value over time.

Operational costs, in simplified terms, can be calculated as the sum of values of two components, i.e., energy consumption costs (e.g. fuel, diesel) and the costs of human labour:

$$\overline{k_u} = \overline{k_{ze}} + \overline{k_u^p} \tag{1}$$

while:

$$\overline{k_{ze}} = \overline{k_{en}^z} \cdot \overline{z_{en}} \tag{2}$$

where:

$\overline{k_u}$ — average cost of a technical object operation per time unit,

$\overline{k_{ze}}$ — average energy cost per time unit,

$\overline{k_u^p}$ — average labour cost of the personnel using the technical object per time unit,

$\overline{k_{en}^z}$ — average purchase price of energy unit,

$\overline{z_{en}}$ — average energy consumption per time unit.

Kumar, Chattopadhyay and Pannu (2004) proposed to consider the readiness of a technical object in addition to specifying the aforementioned two components of the operational cost. The formula for operational cost estimation in the n-th time unit should have the following form:

$$K_U = W_G \cdot C_E \cdot \overline{k_u} \tag{3}$$

while:

$$W_G = \frac{\overline{c_{nz}^m}}{\overline{c_{nz}^m} + \overline{c_{nz}^p}} \tag{4}$$

where:

K_U — operational costs of a technical object in the n-th time unit,

W_G — the technical object readiness index,

C_E — exploitation period (service life) of a technical object per n-th time unit; exploitation period can be expressed by, e.g., mileage, number of hours of operation, calendar time, clock time, etc.,

$\overline{c_{nz}^m}$ — average time between the failure of a technical object caused by corrective or preventive maintenance,

$\overline{c_{nz}^p}$— average downtime of the object operation caused by the need to perform corrective or

[2] The cost parameter is defined by mathematical formulas containing functions and constant values. The parameter cannot represent the sum of other costs (Szkoda, 2007).

preventive services.

$$KU = KZ \cdot W_G \quad (5)$$

while:

$$W_G = \frac{\overline{c_{ok}^d}}{\overline{c_{ok}^d} + \overline{c_{ok}^p}} \quad (6)$$

where:

KU — operational costs incurred during the life cycle of the technical object,

KZ — purchase price of the object,

$\overline{c_{ok}^d}$ — average time of operation till failure,

$\overline{c_{ok}^p}$ — average downtime of the object caused by its failure.

It is worth adding at this point that — depending on the type of an object — the cost of energy consumption is measured in different ways. For example, the standards O-CR-001 (Norsok Standard, 1996a) and O-CR-002 (Norsok Standard, 1996b) provide formulas for calculating energy by the devices in which the power demand is constant and independent of production, whereas the studies by Dhillon (1989) and Monteith (1984) present the cost estimation method of fuel consumption for an aircraft and an engine.

In many scientific papers and publications addressing the LCC analysis (e.g., Bernat & Zieliński, 2006; Bonca & Sieniuc, 2005a, 2005b; Cieślak, 2008; Koniszewski et al., 2009; Palka-Wyżykowska, 2008; Szul, 2011; Hydraulic Institute or Europump, 2001; Świderski, 2003; Kutut et al., 2008; Man et al., 2011) the exploitation cost is the same as the cost of energy. In the LCC analysis, these costs are perceived as fixed over time. In fact, however, their level depends, e.g., on the method of using technical objects and the habits of their users, as well as energy prices within the calculation period. Energy costs in the LCC analysis are determined at the end of each year's forecast. These costs are either discounted (Bernat & Zieliński, 2006; Cieślak, 2008; Koniszewski et al., 2009; Szul, 2011; Pasierb et al., 2008; Świderski, 2003; Hydraulic Institute or Europump, 2001) or not (Bonca & Sieniuc, 2005a, 2005b; Palka-Wyżykowska, 2008; Pasierb et al., 2008) against the base year of the analysis.

2. Methodological approach

The conducted investigation, which followed after collecting and organising information on cost estimation of a technical object operation, resulted in a proposal to use the calculation procedure consisting of eight stages for cost forecasting (Fig. 1). The method estimates cost parameters, using the central tendency values and the values of lower and upper quantiles, which allows estimating costs in three variants: the expected (e.g., modal), the optimistic and the pessimistic.

The procedure starts with defining the division structure of an operational cost, i.e. the cost components and the included parameters. The operational cost structure is described by the following correlation:

$$KU = \langle K_A, K_{AB} \rangle \quad (7)$$

where:

K_A — the set of operational cost components,

K_a — a-th operational cost component, where $a = 1,2,\dots,A$,

K_{AB} — the set of parameters assigned to the set of operational cost components,

K_{ab} — b-th parameter of a-th operational cost component, where $b = 1,2,\dots,B$.

The second stage consists of defining the same length (span) of time intervals, $\Delta t^1 = \Delta t^2 = \ldots = \Delta t^D$, while $d = 1,2,\dots,D$, where d stands for the time interval number, whereas D represents the number of intervals. The range span is the difference between the upper t_g^d and lower t_d^d time interval value. The range is bounded top, with the upper limit in the given range being the same as the lower limit of the next range.

The third stage of the method covers calculating the mean value of the b-th parameter included in the a-th operational cost components for the d-th time interval. The estimated mean values of the parameter are assigned at the upper limits of the d-th time interval, i.e., t_g^d.

The fourth stage of the method is focused on analysing the correlation occurrence between time — Y and the mean values of the b-th parameter of the a-th operational cost component calculated in the d-th time intervals — X. For this purpose, the correlation coefficient estimator ρ can be used between the two examined attributes in the population, i.e., the correlation coefficient from the r sample (Greń, 1982):

$$r = \frac{\sum_{d=1}^{D}(x^d - \bar{x}) \cdot (y^d - \bar{y})}{\sqrt{\sum_{d=1}^{D}(x^d - \bar{x}) \cdot \sum_{d=1}^{D}(y^d - \bar{y})}} \quad (8)$$

where:

x^d — X variable value, i.e. mean value of the b-th parameter of a-th operational cost component in the d-th time interval,

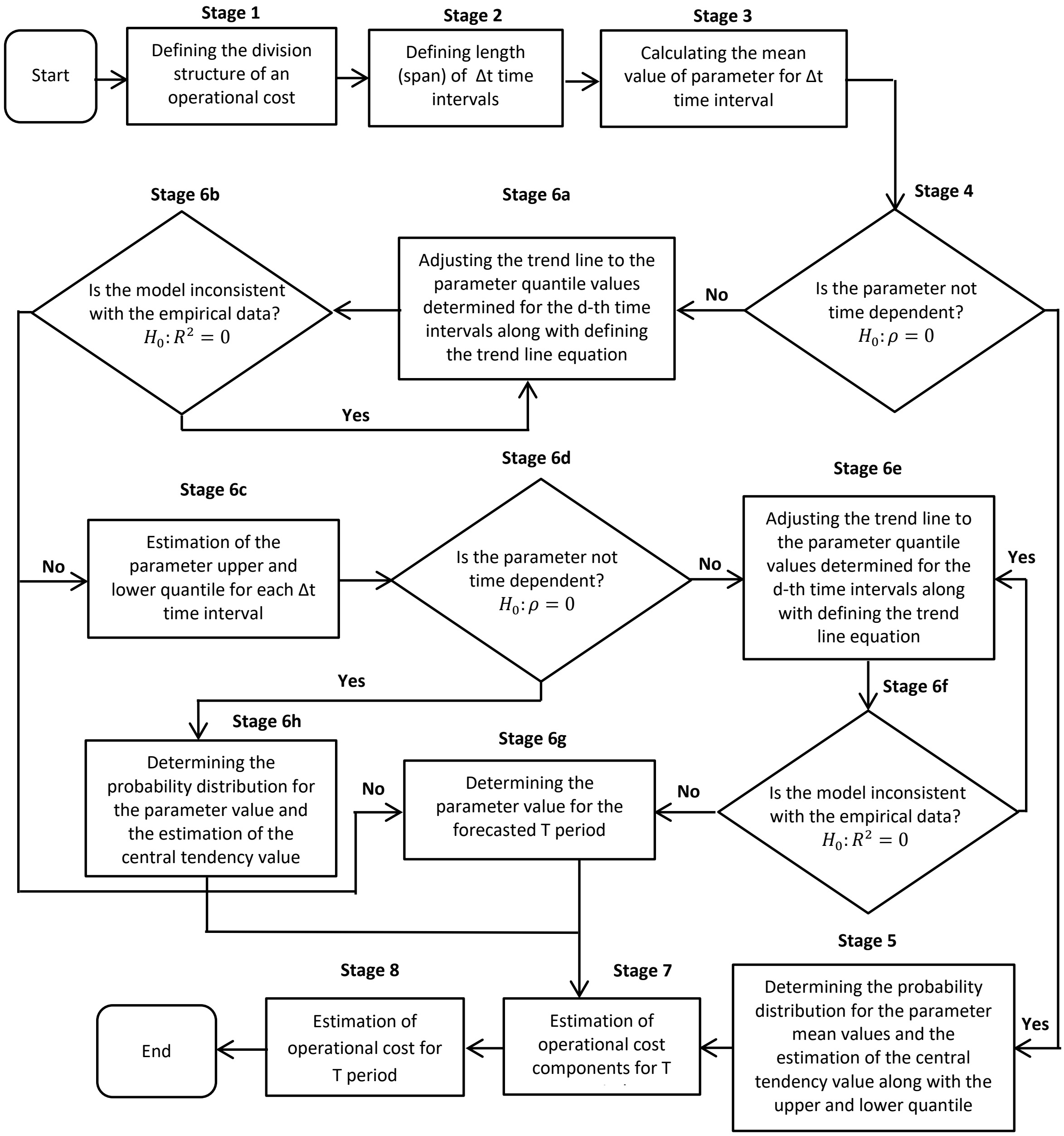

Fig. 1. Algorithm followed in the method for forecasting the costs of a technical object operation

y^d — Y variable value, i.e. time reflected by the upper limit of the d-th time interval t_g^d,
$\bar{x}$ — arithmetic mean X variable,
$\bar{y}$ — arithmetic mean of Y variable,
D — number of observations, the same as the number of time intervals.

To verify the significance of the correlation coefficient, the hypothesis that X and Y variables are not correlated should be checked, i.e., the null hypothesis $H_0: \rho = 0$, against the alternative hypothesis $H_1: \rho \neq 0$. Student's t-distribution for the predetermined α significance level and for $D-2$ degrees of freedom shows $t_\propto$ critical value, so that $P\{|t| \geq t_\propto\} = \propto$. If the comparison of t value is calculated based on formula (9), i.e.,

$$t_{(\propto, n-2)} = \frac{r}{\sqrt{1-r^2}} \cdot \sqrt{D-2} \quad (9)$$

with $t_\propto$ critical value results in $|t| \geq t_\propto$ inequality, then H_0 hypothesis about the absence of correlation between the variables has to be rejected. However, when $|t| < t_\propto$, there are no grounds to reject the H_0 hypothesis, that X and Y variables are uncorrelated.

In the case when it is unfounded to reject the H_0 hypothesis, the theoretical distribution functions (stage five) have to fit the mean values of the b-th parameters of the a-th operational cost components defined for the d-th time intervals. For the probability distribution fitting of X variable, any central tendency value should be determined, i.e., the expected value, modal value or median as well as the lower $F(x_q)$ and upper quantile $F(x_{1-q})$. q order quantile for $0 < q < 1$ takes x_q number, which meets the condition:

$$F(x_q) = \int_{-\infty}^{x_q} f(x)dx = q \quad (10)$$

where:

$F(x)$ — cumulative distribution function of X random variable,

$f(x)$ — probability density function of X variable probability.

If there are grounds to reject H_0 hypothesis, the trend line (stage 6a) should fit the mean values of the b-th parameter defined for the d-th intervals. Stage 6b consists in examining the model compliance with empirical data using R^2 coefficient of determination (Dittman, 2003):

$$R^2 = \frac{\sum_{t=1}^{z}(\hat{x_t}-\bar{x})^2}{\sum_{t=1}^{z}(x_t-\bar{x})^2} \quad (11)$$

where:

x_t — cost parameter value in t period,

$\hat{x_t}$ — theoretical cost parameter value in t period,

$\bar{x}$ — mean value of cost parameter in z time series.

To verify the coefficient significance, statistics F should be used (Dittman, 2003):

$$F = \frac{R^2}{1-R^2} \cdot \frac{D-k-1}{k} \quad (12)$$

where:

D — number of the dependent variable observations (the same as the number of classes),

k — number of predictor variables in the model excluding the variable with the intercept,

which has Fisher–Snedecor F distribution with $k_1 = k$ and $k_2 = D - k - 1$ degrees of freedom, whether the model is inconsistent with the empirical data, i.e., $H_0: R^2 = 0$ null hypothesis against the alternative $H_1: R^2 \neq 0$ hypothesis. If F value is smaller than $F_\propto$ from Fisher-Snedecor F distribution tables for the adopted $\propto$ significance level and also for $k_1 = k$ and $k_2 = D - k - 1$ degrees of freedom, there are no grounds to reject the H_0 hypothesis, which means that the coefficient of determination is not significantly different from zero — the model fit to empirical data is far too weak. In this case, such a trend model of the analysed parameter should be found, for which F statistics can show a correlation occurrence between the data (stage 6a). However, if the coefficient of determination is statistically different from zero, the lower $F(x_q)$ and upper quantile values $F(x_{1-q})$ of the b-th parameter of the a-th operational cost component for each Δt time interval should be determined (stage 6c). Next, in the course of stage 6d, the correlation occurrence between Y time and the defined lower $F(x_q)$ and upper quantile values $F(x_{1-q})$ should be analysed using a correlation coefficient estimator. The hypothesis can be verified using Student's t-distribution with $D - 2$ degrees of freedom. If there are no grounds to reject the H_0 hypothesis, the theoretical distribution function has to fit the quantile values of the b-th parameter of the a-th operational cost component (stage 6h). For the fitted probability distribution of X_q variable, any central tendency value should be defined. However, if there are grounds to reject the H_0 hypothesis, the theoretical distribution functions have to fit the quantile values of the b-th parameter of the a-th operational cost component (stage 6e) and the analysis (stage 6f) — using R^2 coefficient of determination — of the developed model compliance with empirical data has to be conducted. The assessment of correlations is performed by testing $H_0: R^2 = 0$ and $H_1: R^2 \neq 0$ hypotheses. The hypothesis can be verified using statistics which has Fisher–Snedecor F distribution with $k_1 = k$ and $k_2 = D - k - 1$ degrees of freedom. If there are grounds to adopt $H_0: R^2 = 0$ null hypothesis, then such a trend model of the analysed parameter should be defined, for which F statistics will determine the correlation occurrence between the data (stage 6e). In the case when R^2 coefficient of determination is statistically different from zero both in stage 6b and 6f, then in the course of stage 6g, the future value of the b-th parameter of the a-th cost component is determined. This value is obtained by extrapolating the trend function, i.e., by substituting time variable in the model with t moment number or T period for which the forecast is prepared.

The seventh stage consists of the estimation of cost components. The estimation of cost components is based on analytical expressions defined in the second part of the article or by the researcher. The cost component value estimated for the entire life cycle of the T technical object, for which at least one of the parameters remains time-dependent is equal to:

$$K_a = \sum_{t=1}^{T} K_{a_t} \quad (13)$$

Whereas the cost component value for the T entire life cycle of the technical object, for which none of the parameters depends on time should be determined based on the following correlation:

$$K_a = K_{a_{t=1}} \cdot T \quad (14)$$

Stage eight is focused on summing up the cost components included in the operational cost:

$$KU = \sum_{a=1}^{A} K_a \quad (15)$$

3. Conducting the research and results

3.1. Object and period

The method for forecasting the costs of a technical object operation was made for eight single-mode railbuses of type X (manufactured by the same producer), which are a homogeneous set of objects in terms of construction solutions. The railbuses are owned by the Lower Silesia Marshal's Office and operated by a regional rail carrier. Because of a signed statement regarding data confidentiality, the name of the rail carrier could not be disclosed, and the marks (inventory numbers) of vehicles had to be changed.

Some analysed railbuses were taken by the analysed company from another railway company, and others were new, bought by the Regional Government and rented to the analysed company. The vehicles were in possession of the analysed company at different times of their life, as illustrated in Fig. 2.

The period of research analysis encompassed 42 months of rail carrier performance, from December 2013 to June 2017.

The analysis period addressed the events and activities recorded from the 1st till the 50th month of the railbus exploitation. The exploitation time covered by the study was not identical for all analysed railbuses, i.e., for buses 1, 2 and 3 determining the operational cost parameters was possible from the 9th till the 50th month of exploitation. However, for the buses No. 4 and 5, it was possible from the 1st till the 19th month of exploitation, whereas for other objects from the 1st till the 16th, 13th and 12th month, i.e., for buses 6, 7 and 8, respectively.

3.2. Assumptions

The cost components were estimated, adopting the following assumptions:

- A railbus crew consists of one conductor and one driver;
- The central tendency measure is the expected value of E(X) parameters;
- The adopted horizon of cost forecasting is 50 months;
- The exploitation month is not the same as the calendar month;

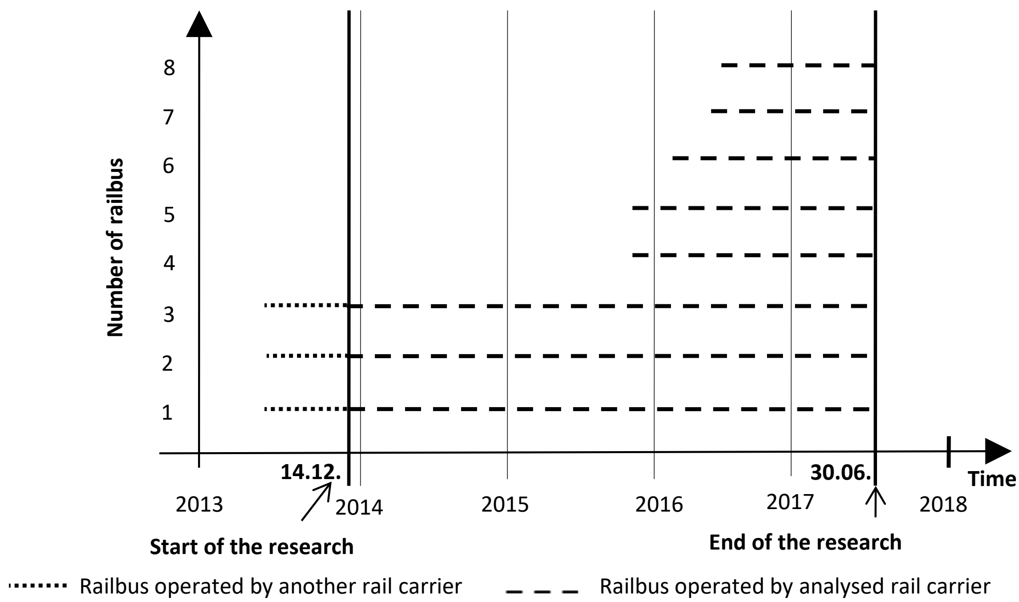

Fig. 2. Schedule of the performed research analysis

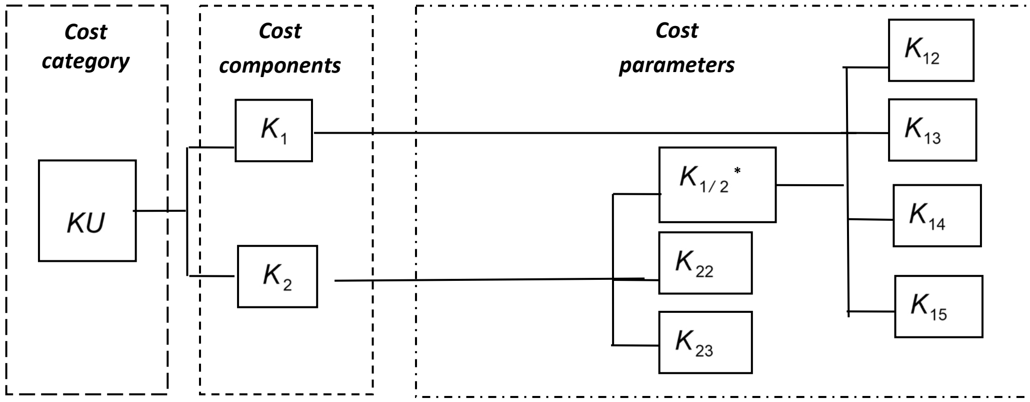

Fig. 3. Structure of costs distribution of a railbus operation adopted for calculations

- When calculating the number of days in the month of exploitation, the calendar year was considered to have 365 days;
- Costs are not discounted;
- The structure of operating costs consists of two components and seven cost parameters included in them (Fig. 3)
- Cost components were defined based on the following formulas:

$$K_1 = K_{1/2} \cdot [(K_{12} \cdot K_{13}) + (K_{14} \cdot K_{15})] \quad (16)$$

$$K_2 = K_{1/2} \cdot K_{22} \cdot K_{23} \quad (17)$$

- The accuracy degree of the operational cost forecast was measured using the ex-post relative forecast error from the formula (Cieślak, 2005):

$$\gamma_t = \frac{KU_t - KU_t^{rz}}{KU_t} \cdot 100 \quad (18)$$

where:

γ_t— ex-post relative forecast error at the end of the Δt time interval,

KU_t — forecasted operational cost value at the end of the Δt time interval,

KU_t^{rz} — actual value of the vehicle operational costs in the Δt time interval.

3.3. Application of the method for forecasting the operational costs of technical objects

The statistical data analysis was performed using the functions and commands available in Microsoft Excel. Weibull++ application was also used, which allowed, e.g.:

- developing histograms and cumulative distribution functions for random variables,
- the verification of hypotheses (carried out using Spearman's rho φ correlation coefficient) in the form of distributions of the analysed random variables,
- the estimation of the unknown distribution characteristics.

For the purposes of the developed method, time series for the operational cost parameters were constructed by averaging the cost parameter per month of railbus exploitation (Fig. 4). In turn, Fig. 5 shows the course of the cumulative distribution function in the probability distribution grid for the operational cost parameters of railbuses.

The list of parameters necessary to estimate the cost components described by formulas (16) and (17) is presented in Table 1. The analysis of the collected information shows that the operational cost parameters are not time-dependent. The analysis indicates that the distributions of daily mileage of railbuses, a train driver's cost of work per 1 kilometre of the route, diesel consumption per kilometre of the route and the purchase price of a litre of diesel can be modelled with a normal distribution — a high value of Spearman's rho φ correlation coefficient was received, ranging from 0.88 to 0.99. In turn, the cost of a conductor's work per kilometre of the route can be described by a log-normal distribution (φ = 0.99). The expected value as well as $F(x_q)$ lower and $F(x_{1-q})$ upper quantile for q=0.05 were determined for the adjusted probability distributions.

The relative errors made when measuring operational costs at the end of the Δt time interval, i.e., the last period, in which the actual costs were recorded, are summarised in Table 2. The prognostic value of the described method is high, as confirmed by the calculated mean value of the relative error module. In forecasting the operational costs of railbuses, the average error was approx. 2.9%.

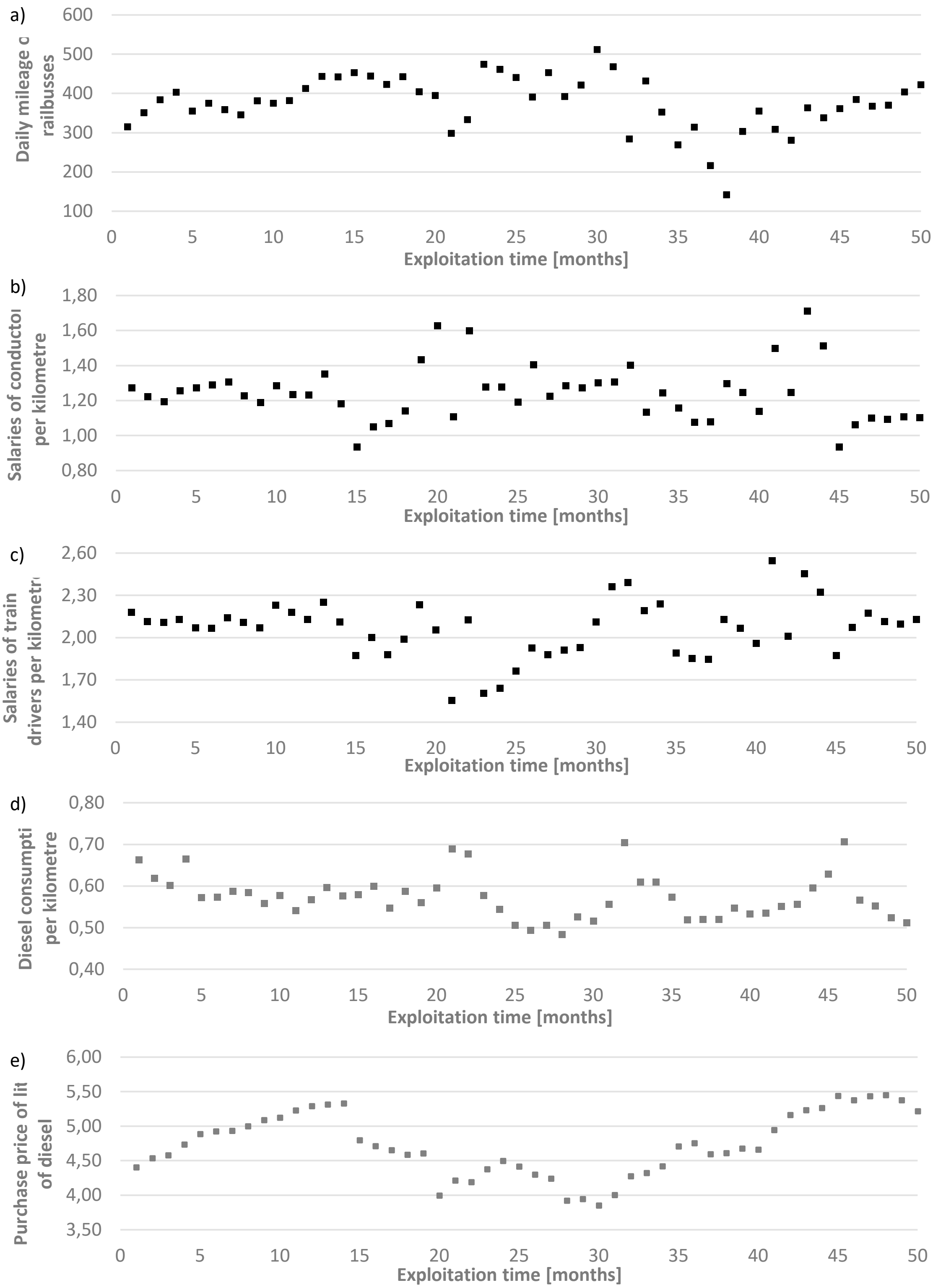

Fig. 4. Data for the time series analysis covering a given operational cost parameter of railbuses: a) daily mileage of railbuses, b) salaries of conductors per kilometre of the route, c) salaries of train drivers per kilometre of the route, d) diesel consumption per kilometre of the route, and e) purchase price of a litre of diesel

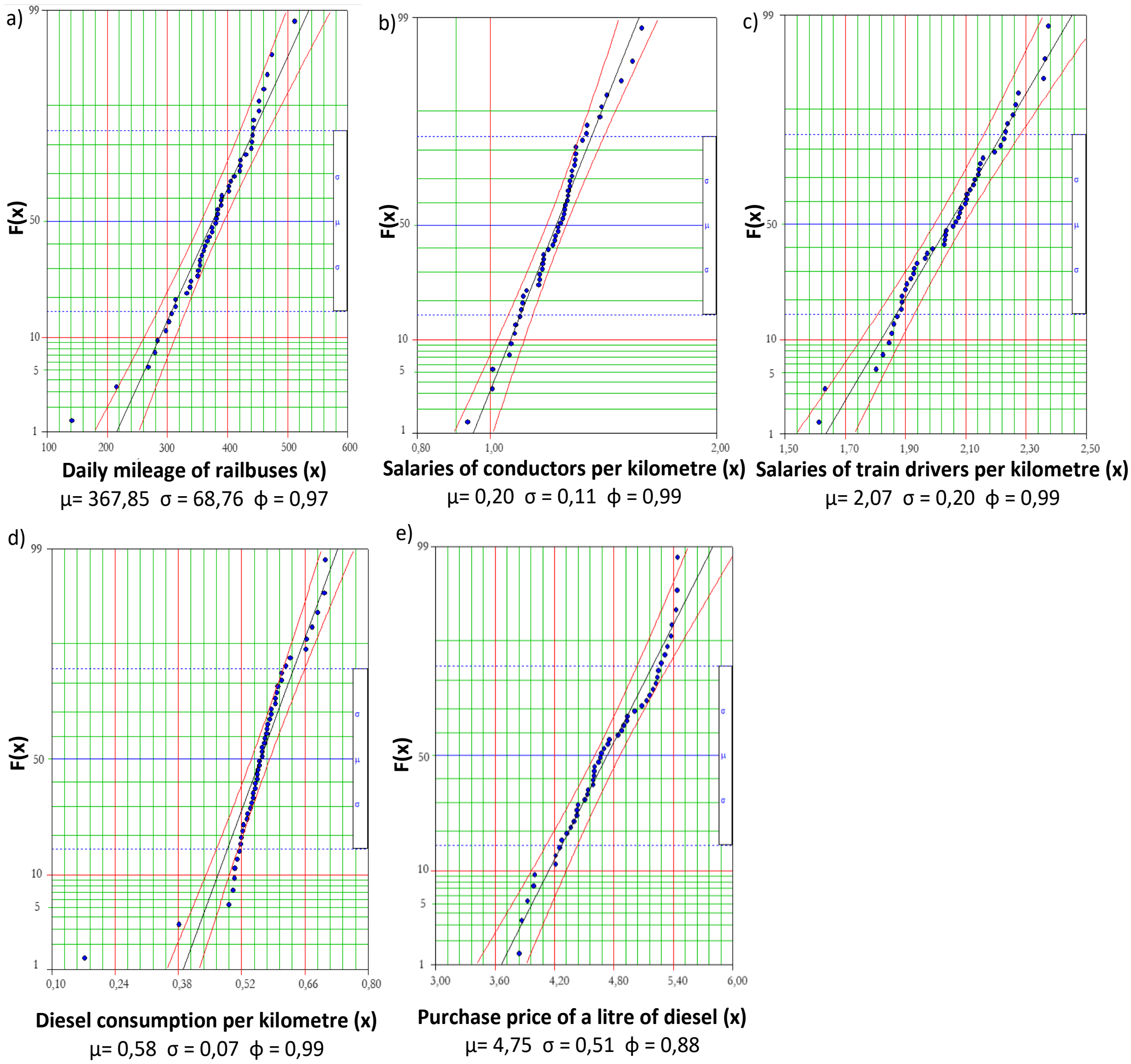

Fig. 5. Distribution of operational cost parameters for test objects: a) daily mileage of railbuses, b) salaries of conductors per kilometre of the route, c) salaries of train drivers per kilometre of the route, d) diesel consumption per kilometre of the route, and e) purchase price of a litre of diesel

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Tab. 1. Parameters of the operational cost components for time intervals presented as the months of vehicle exploitation

		Parameters of the operational cost components				
		$K_{1/2}$	K_{12}	K_{14}	K_{22}	K_{23}
Stage 4	Correlation coefficient (r)	-0.22	-0.07	0.06	0.18	-0.25
	For $\propto = 0{,}05$	t=-1.59 p =0.12 $p > \propto$	t =-0.51 p =0.61 $p > \propto$	t =0.45 p =0.65 $p > \propto$	t =1.27 p =0.21 $p > \propto$	t =-1.78 p =0.08 $p > \propto$
	Accepted hypothesis	$H_0: \rho = 0$	$H_0: \rho = 0$	$H_0: \rho = 0$	$H_0: \rho = 0$	$H_0: \rho = 0$
Stage 5	Type of probability distribution	Normal	Log-normal	Normal	Normal	Normal
	Distribution matching (φ)	0.97	0.99	0.99	0.99	0.88
	$E(X)$	367.85	1.23	2.07	4.75	0.58
	$F(x_{0,95})$	480.95	1.46	2.41	5.60	0.69
	$F(x_{0,05})$	254.76	0.02	1.72	3.91	0.47

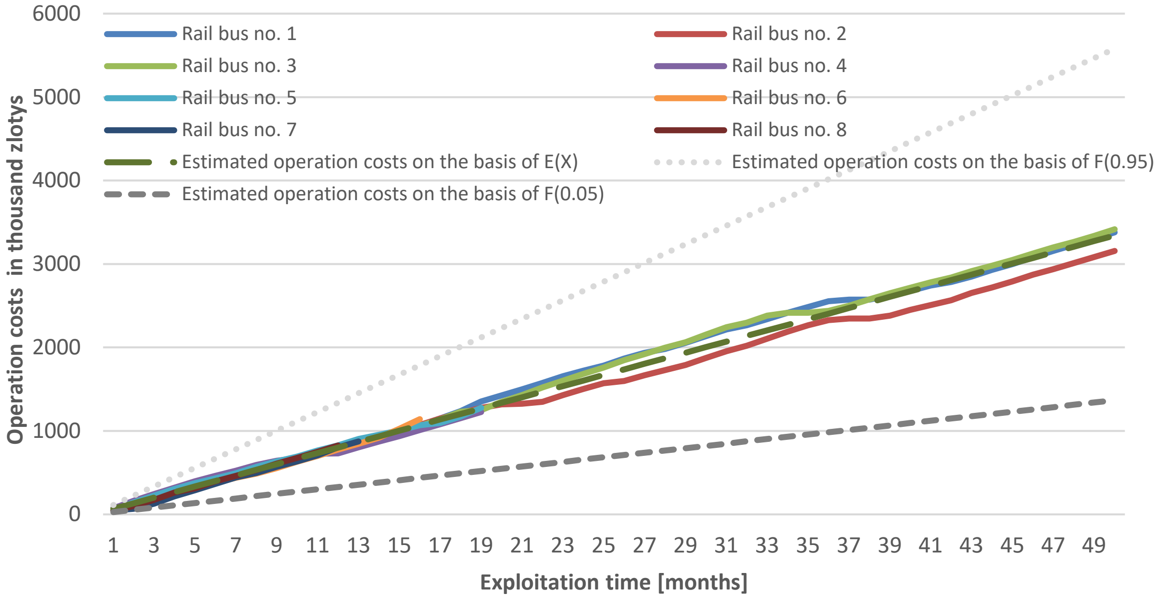

Fig. 6. Cumulative operational costs of railbuses in the analysed period presented as the months of exploitation

Tab. 2. Relative errors in measuring operational costs of railbuses

Railbus number	Last month of the railbus exploitation T	KU_t^{rz}	KU_t	γ_t	Mean relative error
1	50	3379357	3340998	-1.1%	2.9%
2	50	3156515	3340998	5.5%	
3	50	3416362	3340998	-2.3%	
4	19	1226472	1269579	3.4%	
5	19	1276996	1269579	-0.58%	
6	16	1140901	1069119	-6.7%	
7	13	873708	868659	-0.58%	
8	12	825694	801839	-3.0%	

Conclusions

The article discusses the method aimed at forecasting operational costs of technical objects. The presented method allows estimating operational costs in the adopted life-cycle of a technical object. The estimation of costs within three variants, i.e., the expected variant (e.g., modal), the optimistic variant and the pessimistic variant, allows determining the cost range of a technical object operation. It is a universal method, as it can be used for any technical object (provided that the historical data related to the operation of identical objects or homogeneous objects, in terms of their structural solutions, were collected). In addition, this method allows capturing the variability of maintenance costs over time, arising from the gradual changes in object parameters, resulting from technical wear, by examining the correlations of technical parameters such as, e.g., diesel consumption. It should be noted that in the presented method, the level of costs depends on, e.g.:

- the number of components adopted for analysis and the cost parameters identified within them;
- the adopted exploitation time unit;
- the adopted central tendency measure and the confidence interval in the calculations of quantile values.

The analysis of the compliance between forecasted operational costs and the actual costs showed a high correlation, as evidenced by the level of estimated relative errors. Therefore, the method, which was approached as the possibility of its application to estimate operational costs during future periods, has a relatively high prognostic value.

The presented method can also become the basis for estimating total operational costs, which remain an important cost component, considered when assessing the profitability of purchasing one of several competing technical objects offered by the industry. Thus, the modification of the presented method and its implementation constitute the next stage of the author's research covering the LCC analysis.

Acknowledgement

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Risk analysis in maintenance processes

Przemysław Drożyner

ABSTRACT
The article aims to present practical methods for prioritising the activities of maintenance departments based on the Pareto analysis and the failure risk analysis. Based on the collected data on the number of observed failures and their removal times, commonly known reliability indicators were determined, which were then used to estimate the probabilities and consequences of failures in terms of the risk of loss of production continuity. Based on commonly collected failure data, the developed methods allow proposing to the maintenance departments the sequence of maintenance and repair work to be undertaken in terms of minimising the risk of failure. Risk analysis is somewhat commonly used in the practice of maintenance departments (e.g. RBI, FMEA, ETA, FTE, HIRA). The added value of this work is the use of reliability indicators for estimating the values of risk components, i.e., probability and consequences. The method was developed on the basis of operational data collected in one of the plants of the dairy cooperative and, after assessing the effects of its implementation, it was implemented in other enterprises of the cooperative.

KEY WORDS
risk analysis, maintenance, reliability

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Introduction

In ancient times, the failure-free use of technical inventions was the intention of their creators who also understood that this effect was impossible without periodic, more or less complex maintenance activities. Archaeological findings in prehistoric burial places include, e.g., chariots with traces of grease on their axles, and — speaking in modern terms — catalogues of vegetable oils and animal fats to be used as lubricants.

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Throughout history, the concepts of servicing technical facilities have changed. Until the Second World War, such services were mainly understood (apart from cleaning and the aforementioned lubrication) as a reaction to damage. In times of cheap and readily available labour, the reactive approach was predominant. It meant that machines and devices were serviced only when their technical condition required it. Therefore, maintenance activities were most often performed as a reaction to a failure.

In the following decades, machines grew much more complex, making a greater impact on the continuity of production. In the event of a failure, it was no longer possible to replace the operation of these machines with human force, and downtime caused increasingly more economic losses. Along with the increase in the complexity of machine construction, preventive and prognostic concepts emerged, but they still referred to the effectiveness of maintenance activities, i.e., eliminating failures and maintaining the production continuity. Since the end of the last century, the increasing importance of operational efficiency, safety of people and the environment, compliance with the law and standards, and more recently, sustainable development have been recognised.

Maintenance tasks are interdisciplinary. Not only they consist of technical issues (degradation, wear, diagnostics, technical and technological progress) but also legal, normative and managerial issues, which must be resolved to achieve production, quality, environmental and work safety goals. The list of maintenance attributes is no longer limited to the ability to efficiently use workshop tools and quickly locate damage. The contemporary aspects of maintenance include the origin and forecasting of a technical condition, product quality, the safety of people and the environment, and technical and technological development. Such an approach to maintenance processes creates the need to develop or adopt appropriate tools and methods that will allow making effective and efficient decisions regarding the determination of the sequence and scope of maintenance, repair or investment activities.

1. Literature review

The concept of maintenance appears in terms of inevitable costs which, according to various sources, amount to as much as 5% of the company's turnover, constituting 4–15% of the production costs and about 18% of the inventory value depending on the industry (Mikler, 2008). Some sources estimate that the cost of living amounts to 10–40% (Maggard & Rhyne, 1992), 15–50% (Coetzee, 2004), and even 15–70% (Bevilacqua & Braglia, 2000) of production costs. According to Ahlmann (2002), the costs of maintaining machinery in Sweden accounts for 6.2% of the company's turnover. According to Wireman (1990), 30% of the costs incurred for maintenance arise from improper planning of works and related overtime. The actual costs incurred can be much higher.

Machine failure may entail financial losses not only because of the necessity to remove it but also due to the lack of planned production or penalties related to failure to meet deadlines or environmental pollution (Todinov, 2006). Increasingly more often, insurance companies require maintenance, which is safe in the economic, environmental and health-and-safety terms, basing insurance rates on the effectiveness of this process. Enterprises with high organisational and technical culture are therefore changing their attitude to maintenance processes and ceasing to classify them as costs that need to be minimised, perceiving them as costs that can and must be managed instead. Concepts of proactive maintenance, such as TPM, RCM, RBI, consist of monitoring the technical condition of machines, introducing technical diagnostics, and device operators. These concepts, as well as various approaches to the principles of maintenance, have been widely described in the literature (Żółtowski & Niziński, 2010; Legutko, 2010; Niziński & Michalski, 2007; Legutko, 2007; Pintelon et al., 2006; Żółtowski & Tylicki, 2004; Żurek, 2004; Szpytko et al., 2003; Swanson, 2001).

Enterprises with advanced organisational culture and technologies recognise that not only maintenance processes may have a significant impact on the production output, costs and quality of the final product but also the safety of people and the environment. Maintenance is perceived as an important element of sustainable development (Szczuka & Drożyner, 2015; Jasiulewicz-Kaczmarek & Drożyner, 2013; Drożyner et al., 2011; Farrington-Darby et al., 2005; Fei & Honghui, 1998). Maintenance services are becoming an indispensable element of most business processes, such as production planning to ensure continuity, logistics and sales, environmental protection or HR processes (competences, authorisations, staff working hours), including occupational health and safety.

Besides, maintenance services are responsible for (right and wrong) decisions regarding required maintenance and repair activities, such as machine inspection, alignment or balancing. Their choice of an operation strategy or purchasing policy may either positively or negatively influence technical and technological development and, as a consequence, the efficiency and effectiveness of the entire enterprise. Therefore, maintenance is a part of such standards as ISO 55001:2014 on asset management. The guidelines for the implementation of an asset management system contained in the ISO 55002 standard suggest the use of such methods and tools as RCM, FMEA, HAZOP, and RCFA (Root Cause Failure Analysis). The comparison of the requirements of ISO 9001 and ISO 55001 in terms of maintenance processes and, more broadly, operation reveals that infrastructure (physical assets) is treated objectively in the ISO 9001 standard (as an intermediary). In contrast, ISO 55001 treats the assets as the main subject and the purpose of action.

The quality standard refers to the infrastructure instrumentally as one of many factors influencing the quality of the product or service. The requirements for infrastructure generally relate to the effectiveness of maintenance, which aims to ensure timely service considering the risk of a potential failure and downtime, and, sometimes, also the quality requirements for the product, which is potentially at risk due to inadequate technical condition of the facility. The process approach to these issues — although ensuring greater operational efficiency — is not required directly and is the sole decision of the entrepreneur.

The ISO 55001 standard specifies all elements of the process approach to infrastructure management, i.e., requirements for the setting (organisation context), planning, identifying measures, and ensuring resources. Also, it concerns typical systemic actions, such as internal audits, management reviews, corrective, preventive and improvement measures. The standard considers assets as a value that can and must be managed rather than inevitable costs. This standard is in line with the proposed (Jasiulewicz-Kaczmarek & Drożyner, 2011; Jasiulewicz-Kaczmarek & Drożyner, 2013; Drożyner et al., 2013) and the model of machine maintenance processes.

Companies that have implemented formalised management systems for quality, environmental protection, health and safety, etc., are obliged to meet the requirements of relevant standards for continuous improvement. Various tools and methods are used in such activities, e.g., brainstorming, histograms, 5 Whys, the Pareto analysis, the Ishikawa diagrams, and the G8D method (Starzyńska et al., 2010; Mazur & Gołaś, 2010). These tools are generally used to improve management and production processes, and, rarely, auxiliary processes, such as maintenance. Meanwhile, a good product is not enough for a business to maintain a position in the market. Nowadays, competition demands greater efforts, and enterprises that do not minimise losses in production have difficulty with staying in the market (Jasiulewicz-Kaczmarek, 2013; Stanek et al., 2011; Saniuk et al., 2015). Therefore, cost optimisation should apply to all processes, especially those that may generate high costs (Stuchly, Jasiulewicz-Kaczmarek, 2014; Pałucha, 2015; Knights, 2001; Obora, 2008).

The widespread use of classical analysis tools for maintenance processes began with the advent of the TPM (Total Productive Maintenance) concept. The tools are used in maintenance to analyse the causes of damage (5 Whys, the Ishikawa diagram (Chang & Lin, 2006)), the prioritisation of maintenance activities (the Pareto analysis (Borris, 2006)), the process improvement (brainstorming (Drożyner & Hoffa, 2015)). The tools have been practically used in the railway (Kumar et al., 2008), aviation (Al-kaabi et al., 2007; Vassilakis & Besseris, 2009), automotive (Holtz & Campbell, 2003), metallurgy (Gajdzik, 2014) and petrochemical (Prasanna & Desai, 2011) industries.

The maintenance of machinery and equipment depends on the context of the enterprise, its goals, structure, internal limitations and external conditions. Components of the maintenance are the result of (1) units targeted by activities, i.e., specific machines and their modules that require inspection, maintenance, and repair; (2) the company's status in relation to the environment, in which it operates; (3) goals that reflect the strategic importance of the company's maintenance; (4) profile of maintenance tasks; and (5) the results achieved in relation to the expected value. The effectiveness of maintenance management in the enterprise is significantly impacted by such factors as the risk assessment of emergency events, the selection of an operational strategy, and the determination of time intervals and resources necessary to implement the tasks resulting from the adopted strategy (Jasiulewicz-Kaczmarek & Bartkowiak, 2016). The new trend of maintenance management has shifted from time interval-based maintenance to risk approach-based maintenance. Risk assessment integrates reliability with safety and environmental issues and can, therefore, be used as a decision-making tool in preventive maintenance planning (Ratnayake & Antosz, 2017; Gill, 2017; Gallaba et al., 2019; Hameed et al., 2019; Özcan et al.,

Tab. 1. Risk analysis tools used for maintenance

Risk Tool	Description	sample publications on the issue
ETA	Event Tree Analysis — a method for describing the consequences of the superior event, illustrating the progression of events from the initial event to the final event, with particular emphasis on the moments that are decisive for the condition of the facility (installation). It is the primary method of creating an object model for threat analysis	Ahmadi et al., 2008; Mareş et al., 2017
FTA	Fault Tree Analysis — a qualitative method of risk analysis using the structure of logical trees, allowing for modelling the course of a failure and then its analysis. An FTA diagram illustrates causes, the result of which are referred to as uncertain events or risk	Gharahasanlou et al., 2014; Vaurio, 2010
FMEA	Failure Modes Effects Analysis — a method that consists of analytically determining the cause-and-effect relationships of potential product defects and considering the criticality (risk) factor in the analysis. Its aim is to consistently and systematically identify potential product/process defects, and then eliminate them or minimise the related risk	Sutrisno et al., 2015; Onodera & Katsushige, 1997; Braaksma et al., 2013; Mikołajczyk, 2013; Mańka, 2015; Ennouri, 2015
HAZOP	Hazard and Operability Studies, in other words, the analysis of threats and operational capabilities, is based on the PN-IEC 61882 standard. It is often used in the design of new facilities and installations, modernisation of facilities, installations or processes	Hu et al., 2012; Crawley &Tyler, 2015
HIRA	Hazard Identification and Risk Assessment — risk assessment tool that can be used to assess which hazards pose the greatest risk in terms of how likely they are to occur and how great their potential impact may be	Purohit et al., 2018; Liberti et al., 2015
GOFA	Goal-Oriented Failure — analysis and a hazard identification technique that uses selective features from Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) to identify the causes of failure of a specific target	Yi et al., 2017; Yi et al., 2016
RBI	Risk-Based Inspection — determining the scope and methods of testing, allowing to determine the risk associated with the operation of technical devices, based on the results of quantitative risk analysis	Arunraj & Maiti, 2007; Khan et al., 2004; Khan & Haddara,2003
RCM	Reliability-Centred Maintenance — determining the necessary maintenance activities in the operational efficiency of the machine or device, considering the conditions of use	Hauge et al., 2001; Braglia et al., 2019

2019; Michalak, 2017). Risk-based maintenance planning minimises the probability of a system failure and its consequences related to safety, economy and the environment (Jasiulewicz-Kaczmarek et al., 2020). It assists management in making the right maintenance investment decisions, which, in turn, results in better use of existing production equipment. In recent years, there has been a growing interest in the use of risk analysis and risk-based (informed) approaches for guiding decisions on maintenance (Table 1).

2. Research Methods

One company from the food processing industry (dairy) was used to compile data on the frequency and duration of emergency downtime. During the analysed period (20 months), 132 defects were recorded, the removal of which took a total of 241 hours (Table 2).

First, a Pareto analysis was performed for the damage that occurred, considering first the time of their removal and then, their number as a criterion. When conducting the analysis, two variants of the procedure were considered. In the first one (V1), each operated device was studied separately. In the second (V2), whole homogeneous groups of devices (such as tanks) were studied separately (as a single unit). As the Pareto analysis is widely described in the literature (Karuppusami, Gandhinathan 2006; Talib et al., 2010; Miller 2011), the description is not provided in this paper. The results of the analysis are presented in Figs. 1–4.

Tab. 2. List of the frequency and duration of emergency downtime at the enterprise

Equipment	Units of equipment	Code of equipment	Number of failures N_i in the analysed period	Number of failures per equipment	Total time T_i of damage removal [h]	Time T_i of damage removal for single equipment [h]
horizontal tank	7	hori	35	5	70	2
submersible pump	20	subm	40	2	40	1
washing station	2	wash	8	4	24	3
condensing unit	1	cond	5	5	15	3
water boiler	1	wate-b	5	5	10	2
shrink wrapping machine	1	shri	3	3	9	3
pneumatic pump for cheese	1	pneu	3	3	9	3
centrifuge LWG-47	1	cent	3	3	9	3
pneumatic press of cheeses	1	pneu1	4	4	8	2
milk collection station	1	milk	4	4	8	2
cheese cauldron	1	chee-c	3	3	6	2
vacuum packing machine	1	vacu	3	3	6	2
cheese slurry pump	1	chee-s	3	3	6	2
hot water pump	3	hot	3	1	6	2
water cooler	1	wate-c	2	2	6	3
pasteuriser - milk - cream	1	past	4	4	4	1
centrifugal pump	1	centp	2	2	2	1
screw compressor	1	scre	1	1	2	2
elevator	1	elev	1	1	1	1
together			132	58	241	40

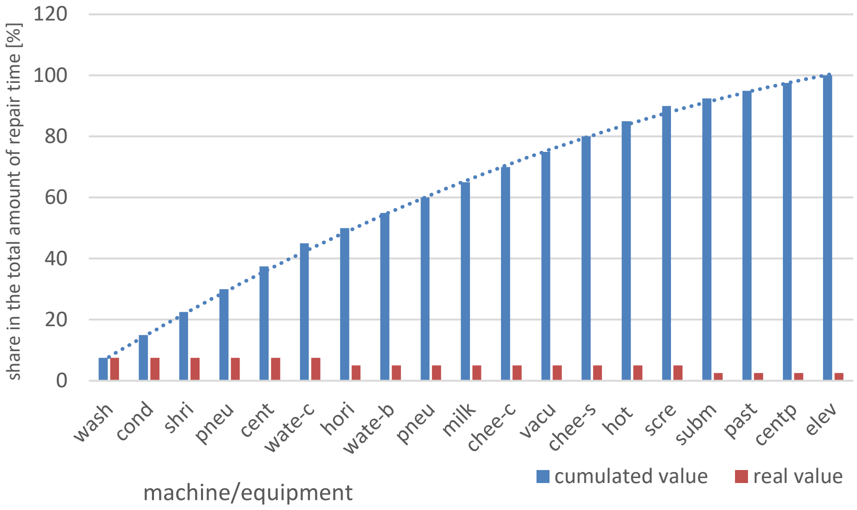

Fig. 1. Result of the Pareto analysis for the "repair time" criterion in the V1 variant

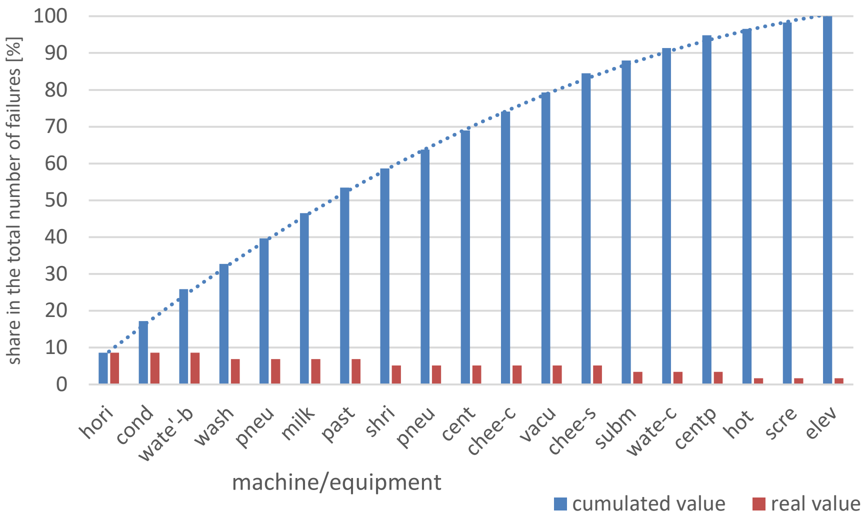

Fig. 2. result of the Pareto analysis for the "number of failures" criterion in variant V1

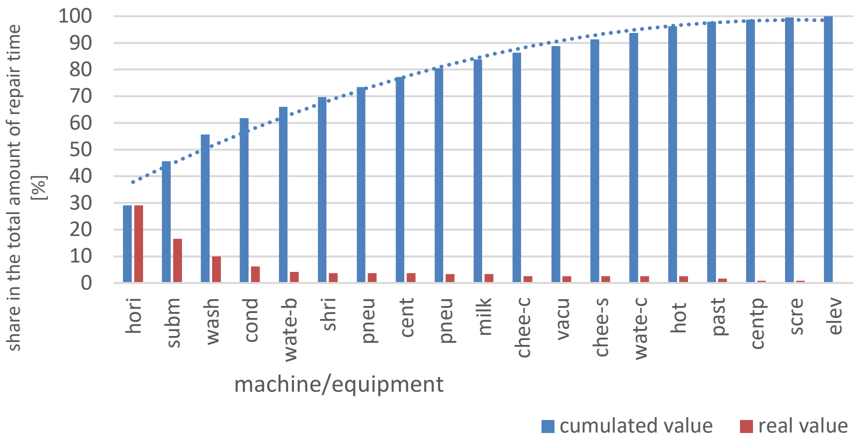

Fig. 3. Result of the Pareto analysis for the "repair time" criterion in the V2 variant

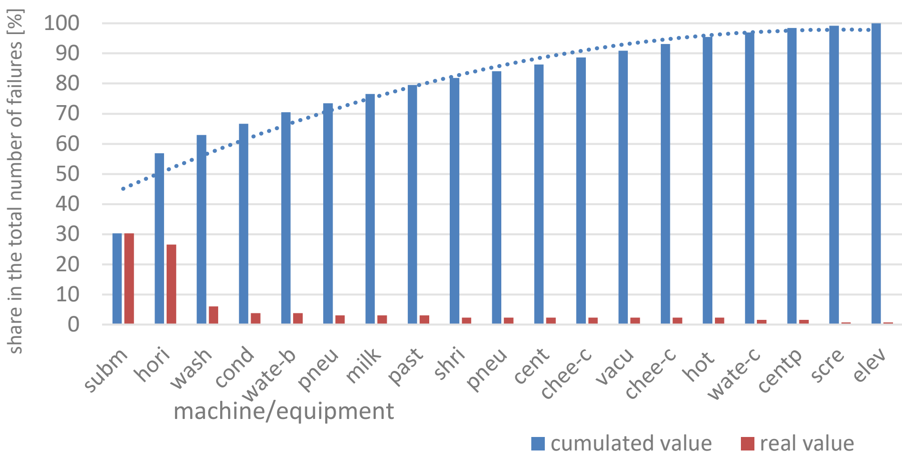

Fig. 4. Result of the Pareto analysis for the "number of failures" criterion in the V2 variant

It was found that in variant V1, when using the repair time criterion, the most important damages with the total share in the criterion of 80% were those that happened at the washing station, the condensing unit and the shrink-wrapping machine. In the case of the failure number criterion, the most important damages were those that were found at the horizontal tank, condensing unit and water boiler. In variant V2, when using the repair time criterion, the most important damages were those that took place were at the horizontal tank, submersible pump and washing station. And using the criterion of the number of failures, the most important damages were those that occurred at the submersible pump, the horizontal tank and the washing station. In the next step, it was decided to carry out the analysis using the method proposed by Knights (2001). This method allows for the simultaneous study of the influence of two criteria as opposed to the traditional Pareto method, where the influence of only one factor can be determined and visualised at one time, as shown in Figs. 1–4.

Figs. 5 and 6 show the location of individual pieces of equipment (their codes) in the coordinate system "number of failures" and "repair time" for both variants of analyses. This type of analysis allows for a certain grouping of equipment from the point of view of the product depending on the frequency and duration of failures. It is possible to easily visualise pieces of equipment, for which failures are chronic (relatively frequent) and those that, even in the case of a single incident, are significant for the company (due to the time required for removal). It was assumed that the threshold value of the number of failures L for chronic failures is:

$$L = \frac{N}{p} \tag{1}$$

where:
N — total number of damage incidents,
p — number of pieces of equipment (19 in variant V1 and 47 in V2),
and for severe damage, the average repair time K is:

$$K = \frac{T}{N} \tag{2}$$

where:
T — total damage removal time.

For the collected data, L = 6.9 failures per piece of equipment and K = 1.8 h per failure in variant V1 and L = 2.8 failures per piece of equipment and K = 1.8 h per failure in variant V2 were calculated. These limits are presented in Figs. 5 and 6. Pieces of equipment were classified depending on types of failure, i.e., chronic, major, chronic and serious, and less significant. A logarithmic scale was used to make the chart more readable. "L" — vertical line, "K" — horizontal line.

Based on this approach, the most important pieces of equipment were the shrink-wrapping machine, the centrifuge LWG-47, the pneumatic press for cheeses, the washing station, the condensing unit, the cheese slurry pump, the cheese cauldron, the vacuum packing machine, the pneumatic pump for cheese, the milk collection station, the water boiler and the horizontal tank in variant V1 and the horizontal tank, the submersible pump and the washing station in variant V2. As the use of risk analysis methods is becoming increasingly more

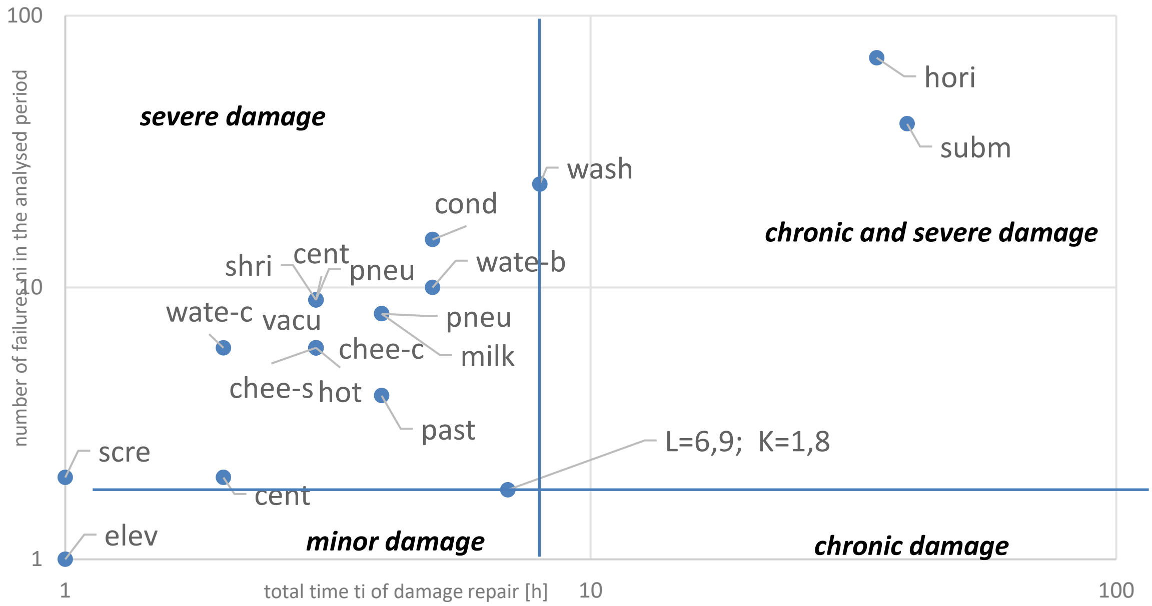

Fig. 5. Tested equipment and the "number of failures — failure recovery time" (V2) system

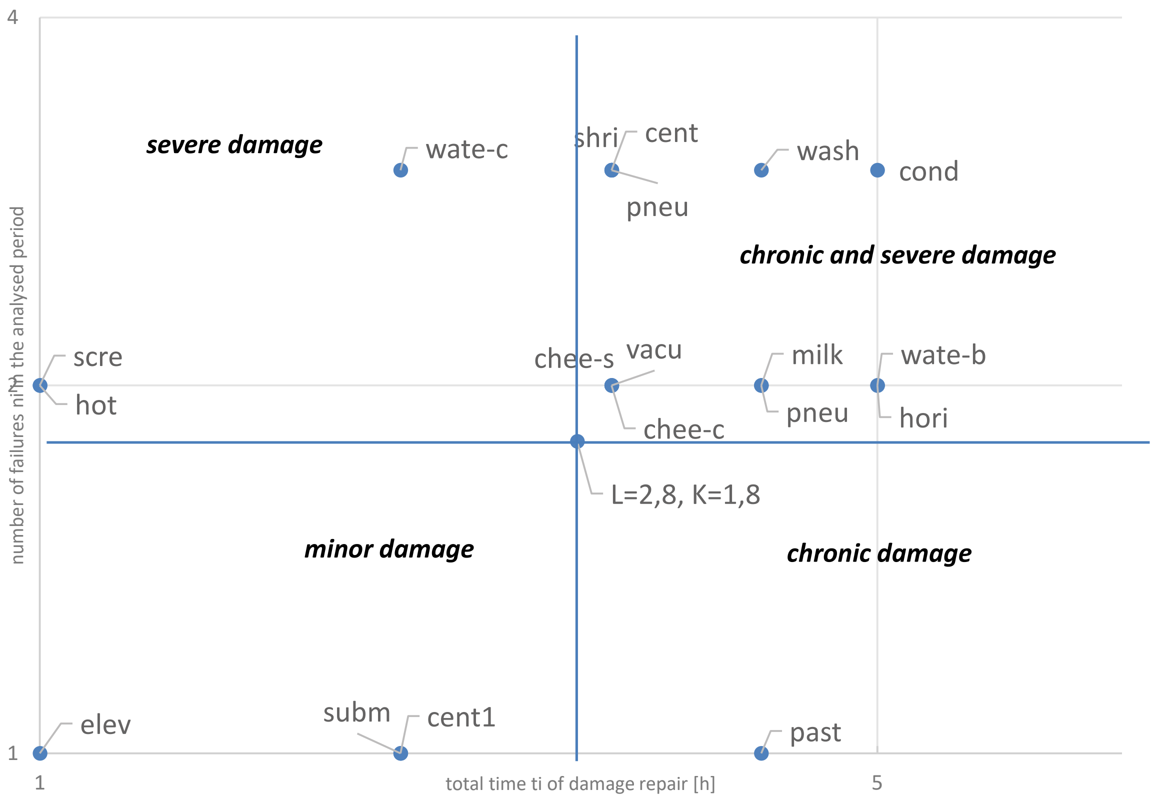

Fig. 6. Tested equipment and the "number of failures — failure recovery time" (V1) system

common for the issues related to machinery and equipment operation, including maintenance (Weber et al., 2012; Aven, 2008; Khan et al., 2004), an original risk assessment method was proposed for further analyses related to failures of individual pieces of equipment with the use of reliability indicators to estimate the probability and consequences of failures. For this purpose, the average times of correct operation between failures for individual pieces (MTBFi) and the share of time ki in repairing the *i*-th device in the total working time of the company in the examined period T_c (based on accounting data, 4 000 hours of operation in the analysed period were assumed) and the damage stream λ_i for the *i*-th device, where:

$$MTBF_i = \frac{T_c}{n_i} \tag{3}$$

$$\lambda_i = \frac{1}{M\ T\ B_i} \tag{4}$$

$$k_i = \frac{t_i}{T_c} \tag{5}$$

It was assumed that the measure of the probability of a failure will be the value of the failure stream λ_i, and a measure of consequence — the share of repair time for a given piece of equipment in the total operating time of k_i. The acceptable risk area (the green area in Figs. 7 and 8) was the area limited by the values of λ_i i k_i equal to 1/3 of the maximum values of λ_i i k_i, respectively $\lambda_{accept} = 0.0033$ and $k_{accept} = 0.0058$ (in the variant V1) and $\lambda_{accept} = 0.000433$ and $k_{accept} = 1.04E-07$ (V2). In turn, the increased risk (the yellow area) is determined (arbitrarily) by values that are twice as high.

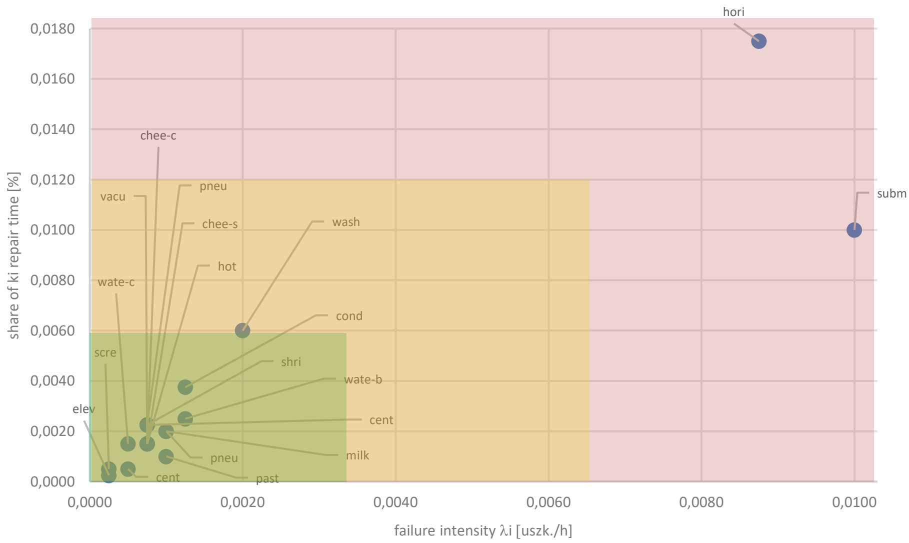

Fig. 7. Risk matrix for the tested devices (V2)

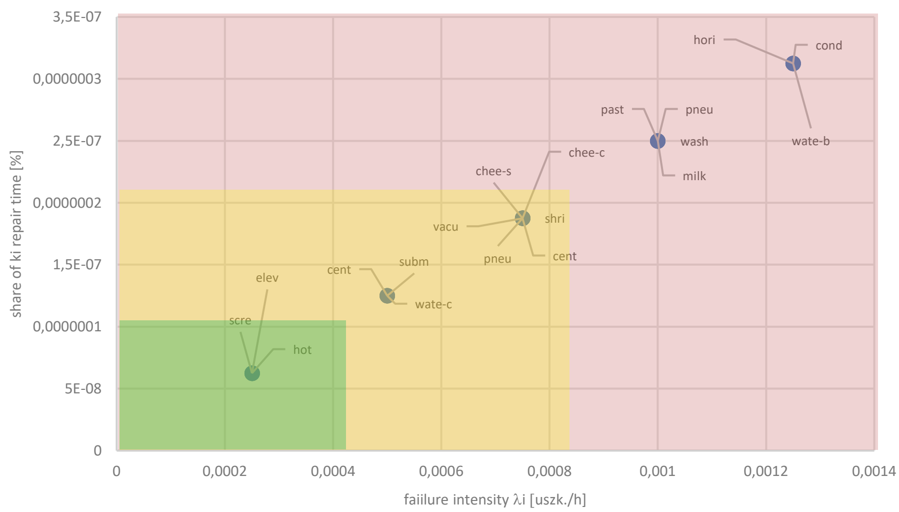

Fig. 8. Risk matrix for the tested devices (V1)

Based on these assumptions, in the V1 variant, the pieces of equipment with unacceptable risk were the pasteuriser for milk and cream, the pneumatic pump for cheese, the washing station, the milk collection station, the condensing unit, the horizontal tank, the water boiler. In the case of the V2 variant, the pieces of equipment with unacceptable risk were the horizontal tank and the submersible pump. The results of analyses and calculations are summarised in Tables 3 and 4. The description of the adopted category A for the tested devices is presented in Table 5.

3. Results and discussion

Summarising the results obtained in the conducted analyses, it can be stated that the most rigorous in terms of prioritising the tasks of maintenance services is the method of risk analysis in variant V2, i.e., treating groups of homogeneous pieces of equipment as a single piece. The example of submersible pumps and tanks shows that damage to individual devices is not particularly visible in statistics and analyses, and only the grouping of these devices and

Tab. 3. Summary of the analysis results for variant V1

Category	Equipment qualification in aspect (V1)			
	single-criteria Pareto analysis		two-criteria Pareto analysis	risk analysis
	by repair time	by number of damage incidents		
A	washing station, condensing unit, shrink wrapping machine, pneumatic press of cheeses, centrifuge LWG-47, water cooler, horizontal tank, water boiler, pneumatic pump for cheese, milk collection station, cheese cauldron, vacuum packing machine, cheese cauldron	horizontal tank, condensing unit, water boiler, washing station, pneumatic press of cheeses, shrink wrapping machine, pneumatic pump for cheese, centrifuge LWG-47, cheese cauldron, vacuum packing machine	shrink wrapping machine, centrifuge LWG-47, pneumatic press of cheeses, washing station, condensing unit, cheese slurry pump, cheese cauldron, vacuum packing machine, pneumatic pump for cheese, milk collection station, water boiler, horizontal tank	pasteuriser - milk – cream, pneumatic pump for cheese, washing station, milk collection station, condensing unit, horizontal tank, water boiler,
number of devices	13	10	12	7

Tab. 4. Summary of the analysis results for variant V2

Category	Equipment qualification in aspect (V1)			
	single-criteria Pareto analysis		two-criteria Pareto analysis	risk analysis
	by repair time	by number of damage incidents		
A	horizontal tank, submersible pump, washing station, condensing unit, water boiler, shrink wrapping machine, pneumatic pump for cheese, centrifuge LWG-47	submersible pump, horizontal tank, washing station, condensing unit, water boiler, pneumatic pump for cheese, milk collection station, pasteuriser - milk - cream	horizontal tank, submersible pump, washing station	horizontal tank, submersible pump
number of devices	8	8	3	2

Tab. 5. Descriptions and comparison of the adopted damage category

Category	single-criteria Pareto analysis	two-criteria Pareto analysis	risk analysis
A	damage for which the total share in a given criterion is 80%	severe and chronic damage	damage with an unacceptable risk

their failures shows that they are a serious problem for maintaining the continuity of the company's production. A pure Pareto analysis, especially in the case of small differences in times of correct operation and the number of failures for individual pieces of equipment, is rather of little use as the number of pieces selected in this way is so large that it does not make a significant contribution to the planning of maintenance and repair works.

In maintenance risk analysis tools like RBI or FMEA, fuzzy values such as "very small", "small", etc. are generally used to estimate probability and consequences. Often these values are burdened with a high degree of subjectivity of the authors of these analyzes and result from their personal experiences. In the method proposed in the article, to estimate the probabilities and consequences of damages, "hard" data on times and numbers of failures collected during operation were used. In the method proposed in the article, to estimate the probabilities and effects, "hard" data on the times and numbers of failures collected during operation were used. These data were then processed into commonly known reliability indicators, such as MTBF or failure stream. This means that the adopted values of probabilities and consequences are characteristic of the considered population of machines and devices, and for other populations, they may have completely different values. In this way, it was possible to eliminate the subjectivism of risk assessment and analysis.

Conclusions

The perception of maintenance tasks evolved over time from a purely technical role, focused on strict maintenance and repair activities, through preventive and prognostic concepts to proactive, and even intended to be an element of sustainable development. By analogy with the concept INDUSTRY 4.0, MAINTENACE 4.0 comes into use as a technical, technological and even social equivalent. As a result, maintenance as an interdisciplinary field needs appropriate methods and tools that will allow it to achieve its goals effectively and efficiently.

A characteristic feature of traditional, classic tools used in quality management and process improvement (such as the Pareto analysis or the Ishikawa diagram) is their simplicity, efficiency and practically no cost. They allow the identification of qualitative and sometimes also quantitative relationships between various factors in the production process. Thanks to the use of these methods, it is possible to make decisions that will optimise the use of resources, change the methods of operation and organisation of work, and although they do not create technical or technological progress themselves, they can make a significant contribution. It can be concluded that these tools are mainly applicable to the economic and organisational aspects of maintenance, but they can also identify strictly technical needs, such as creating models for more effective maintenance planning. The article shows how the use of various tools, such as the Pareto analysis, two-criteria Pareto analysis, risk analysis with the use of reliability indicators to estimate the probability of failures and their effects, allows identifying those pieces of equipment whose failures are of key importance for the effectiveness of the production process. It has been shown that the most "restrictive" tool that directs the activities of maintenance services is the risk analysis, which uses operational data that is easy to obtain, i.e., the number of failures and the time required for their removal. It has also been shown that the way of collecting and classifying the collected data is important. Information about the operation of each separate piece should be collected rather than the whole group of pieces operated as one as it may lead to the "blurring" of the problem, which may be important for an enterprise. Naturally, such methods and tools will not make it possible to improve the technical aspect of the maintenance activities related to the prediction and elimination of the effects of various types of wear and fatigue processes taking place in the operated technical facilities. New equipment and methods will be required in such a case, resulting from technological progress and scientific research.

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Exploring critical success factors for the implementation of lean manufacturing in machinery and equipment SMEs

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ABSTRACT
This study aims to explore the predominant critical success factors (CSFs) for the implementation of lean manufacturing (LM) in small and medium-sized enterprises (SMEs) producing machinery and equipment (M&E). The convergent parallel mixed-methods (qualitative and quantitative) were employed in three Malaysian M&E manufacturing SMEs. The study identified four predominant CSFs that significantly impact on the LM application in M&E manufacturing SMEs, namely, leadership and commitment of the top management, training to upgrade skills and expertise, employee involvement and empowerment, and the development of LM implementation framework for SMEs. This study can assist the M&E manufacturing SMEs in prioritising these predominant CSFs so that the management teams can work on the improvement strategy and achieve a higher level of lean sustainability. It offers valuable insights into the LM implementation that could provide a practical reference guide to other industrial companies.

KEY WORDS
lean manufacturing, critical success factors, machinery and equipment, small and medium-sized enterprises

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Introduction

In Malaysia, small and medium-sized enterprises (SMEs) include firms with sales turnover below RM 50 million or the number of full-time employees below 200 (SME Corp. Malaysia, 2020). Manufacturing SMEs always faced challenges in business sustainability and productivity as well as cost issues. Lean manufacturing (LM) is an effective management system which can help enterprises to create value-added activities and eliminate unnecessary waste (Achanga

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et al., 2006; Driouach et al., 2019; Womack et al., 1990). The LM system contributes to operational excellence and improves the quality services (Driouach et al., 2019; Liker, 2004; Shah & Ward, 2002; Ulewicz & Kucęba, 2016; Womack et al., 1990; Yahya et al., 2019). Despite its prevalence in large enterprises (Shah & Ward, 2002), several surveys showed inconsistent adoption across industries and countries (Abu et al., 2019; Khusaini et al., 2014; Nordin et al., 2013; Shah & Hussain, 2016). Many SMEs either have not adopted LM (Achanga et al., 2006) or still struggle to introduce LM into their processes (Driouach et al., 2019). Malaysian sectors manufacturing machinery and equipment (M&E) are classified into four major sub-sectors (Malaysian Investment Development Authority (MIDA), 2019):

- Specialised process machinery or equipment for a specific industry;
- Metalworking machinery;
- Power generating machinery and equipment;
- General industrial machinery & equipment, components, and parts.

M&E sectors in Malaysia have shown a tremendous contribution to the total export of RM 40.5 billion in the year 2018 and has seen a dramatic rise over the past five years. They are expecting to grow at an average annual growth rate of 4.1 per cent to reach RM 43 billion in 2020 (MIDA, 2019). However, the existing literature on LM adoption for M&E in Malaysia only amounts to 2.3%, which is very little as compared to the automotive industry with 37.1% (Osman et al., 2020). Therefore, this study aimed to explore the predominant critical success factors (CSFs) of LM in M&E manufacturing SMEs. Many CSFs, which had been discussed in the previous literature, are generic for all types of organisations. Nevertheless, they may exert different degrees of impact on SMEs depending on the company and industry. Therefore, proper identification of predominant CSFs is essential to increase the chance of success in LM adoption for SMEs. This study will help the management or lean practitioners of M&E manufacturing SMEs to prioritise predominant CSFs so that the lean committee can work on the suitable improvement strategy to move forward and become more sustainable in lean manufacturing. It will be beneficial for SMEs aiming to sustain business, profitability, and growth.

This paper has six sections: the first section introduces the LM adoption in M&E manufacturing SMEs and presents the problem statement. The second section discusses a structured literature review on LM and CSFs for the implementation of LM in SMEs. The research methodology and description of the company profiles are presented in the third section. The fourth section contains the data analysis, which is followed by a discussion of the results in the fifth section. Finally, the last section states the conclusions, implications, and recommendations for future research efforts.

1. Literature review

LM originated in Toyota Production System (Ohno, 1988) and was later popularised by Womack et al. (1990) in their book "The Machine That Changed the World". The essence of the concept is to eliminate non-value-added activities, generally referred to as waste. Ohno (1988) derived seven forms of wastes, which are overproduction, waiting, transportation, excess processing, inventories, motion, and defects. According to Liker (2004), three primary sources of wastes in production are Muda (waste), Mura (unevenness), and Muri (overburden). Womack & Jones (2003) proposed five underpinning lean principles. They start with identifying the value from the voice of the customer and mapping the value stream which specifies the process creating the value; the process should run in a continuous flow to deliver a quality product just in time to the customer; a pull system is used to prevent any overproduction and, finally, the system must be continuously improved in the pursuit of perfection. It is essential to understand these principles well before starting to implement LM (Bakar et al., 2017; Wong & Wong, 2011a, Wielki & Kozioł, 2018). The most substantial challenge encountered by SMEs is to know which principles, tools and practices to implement and how to apply them effectively (Belhadi et al., 2016). People are a critical factor in LM, and having adopted the right approach of "think lean" and "act lean", they form the essential three constructs that support the LM implementation (Wong & Wong, 2011a). Toyota Production System had strongly emphasised the principle of "respect for people" as an essential element for organisations when embarking on an LM programme (Liker, 2004).

CSFs are defined as the limited number of areas in which satisfactory results ensure successful competitive performance (Griffin, 1995). The structured literature review intends to study CSFs for the LM implementation in SMEs. The materials dated 2016–2019 were searched and adopted from online knowledge database sources, such as Google Scholar, Science Direct, ResearchGate, Scopus and Emerald. The main keywords used to search the study area included: "lean manufacturing", "lean", "critical success factors", "SMEs", and "implementation". The papers were examined and sorted to ensure the contents matched the research topic. Other irrelevant papers, such as "lean six sigma", were filtered out, leaving only those that discussed "lean" or "lean manufacturing" topics. As a result, 17 journal articles focused explicitly on SMEs were selected. The LM implementation would move progressively with a strong knowledge of lean philosophy and lean tools (Almanei et al., 2017). Management knowledge is extremely significant in the LM implementation for SMEs (Pearce et al., 2018), as strong management knowledge can buy-in the lean project idea confidently and strengthen the knowledge gaps for their employees to foster lean implementation. Jani & Desai (2016) concluded that management commitment towards the lean concept was essential to ensure that a project or activity achieved management objectives with the right direction of business growth. According to some authors, the LM implementation always faces minor support from the top management, resistance to change by the middle management, and weak or non-qualified lean training programmes (Viagi et al., 2017). Every management level in SMEs is playing an essential role in connecting each other with great teamwork to encourage employee involvement in the lean project. Experienced employees with lean expertise can become the driver for the LM implementation and produce sustainable lean results. The criticality of success factors is progression-dependent and needs a more dynamic model of lean implementation (Knol et al., 2018). Prioritisation of the sequence order of these factors during every different stage of the LM implementation can increase the chances of success. The introduction of the lean through the change in organisational culture is critical, and SME owners or managers need to make sure that this is a part of

Tab. 1. CSFs for the LM implementation in SMEs

CSFs for the LM implementation in SMEs	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Lean knowledge and experiences of the managers		x	x							x	x						
Leadership and commitment of the top management	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Resource capability (financial, time, workforce)	x	x	x	x	x	x		x	x	x	x		x		x	x	x
Change in the organisational culture	x	x	x		x	x	x	x	x		x	x	x	x	x	x	x
Understanding of lean tools and knowledge	x	x		x		x	x	x	x	x	x	x	x	x	x	x	x
Employee involvement, empowerment, and motivation	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
External support from consultants	x	x	x			x			x		x						x
Training, education, and skills	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Effective communication	x			x	x	x	x	x					x	x	x		
Customer focus	x			x		x			x		x		x			x	x
LM implementation strategy plan, goal and vision	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
Performance management system			x	x	x	x		x					x		x		
Technology resource								x		x	x					x	
Government intervention	x								x	x							
Supplier management			x	x		x			x				x		x	x	x
Project management and planning			x			x		x						x	x	x	

Note: A (Almanei et al., 2017); B (Pearce et al., 2018); C (Viagi et al., 2017); D (Knol et al., 2018); E (Alkhoraif et al., 2019); F (Belhadi et al., 2019); G (Pereira & Tortorella, 2018); H (Driouach et al., 2019); I (Belhadi et al., 2018b); J (Nyoni & Bonga, 2018); K (Grigg et al., 2018); L (Belhadi et al., 2017); M (Jani & Desai, 2016); N (Elkhairi et al., 2019); O (Siegel et al., 2019); P (Sahoo, 2018); Q (Belhadi et al., 2018a) critical considerations in the lean transformation strategy (Alkhoraif et al., 2019). The change in organisational culture must have a reasonable timeline to deal with the resistance among employees and to provide them with more chances to get familiar with the changes that occur in the lean transition period.

Belhadi et al. (2019) prioritised CSFs using the analytical hierarchy process (AHP) method and showed that the "policy, leadership and management" category was the most significant for SMEs in the LM implementation. Sahoo (2018) revealed that the alignment to strategy and long-term planning was the most critical factor in determining a successful lean project. Therefore, the management shall demonstrate their strong leadership commitment by establishing the lean policy and overall LM implementation strategy framework direction for other employees to meet the objectives. The CSFs, barriers and lean tools or practices of the processes should be integrated into the LM implementation framework in SMEs (Driouach et al., 2019; Pereira & Tortorella, 2018). The Sustainable Lean Iceberg Model was used to present the vitality of "strategy and alignment", "leadership" and "behaviour and engagement" (Grigg et al., 2018). This clearly showed that the sustainability of the LM implementation in SMEs mainly depended on the top management leadership commitment as well as the LM implementation strategy direction which aligns with the company goal, and the employee attitude and involvement. Employee engagement and the understanding of lean tools and skills can be enhanced through the provision of intensive training. Excellent communication is vital for lean practices because improvements always require active two-way interaction among colleagues, especially when focusing on shop-floor activities (Knol et al., 2018). The lean consultant with a superb knowledge of the subject can avoid confusion in the LM implementation (Almanei et al., 2017). Siegel et al. (2019) stated that employee involvement, management commitment, and measurement and metrics are the essential factors for the success of Green-Lean implementation. The CSFs from the discussed articles (Table 1) show that by employing these factors in the LM implementation journey, SMEs could move progressively towards the success of the lean transformation. Symbol "x" indicates that the CSFs were included in the article's content. The predominant CSFs that are important for the LM implementation in SMEs (Table 1) were identified, i.e., leadership and commitment of the top management, employee involvement and empowerment, lean training and education for employees to acquire the specific skillset, and the development of LM implementation framework. These top four predominant CSFs were selected for further investigation in the studied case of M&E manufacturing SMEs.

2. Research method

Only the M&E companies that corresponded to definitions of the Malaysian manufacturing SMEs were eligible for this study. This research was conducted by using a multi-case study to analyse the selected companies expressing the high interest and willingness to participate. The method of multiple case studies could be used for a good comparison of the common similarity and main differences among the M&E manufacturing SMEs on their LM implementation perspectives and experiences (Creswell, 2014). The general profile of the analysed companies is shown in Table 2. The three analysed companies from the targeted M&E sub-sectors were chosen using the purposive sampling method, as they could provide the information required to achieve the study objective. All companies were operational for more than ten years with different degrees of the LM implementation.

The percentage of research methods used to investigate the LM implementation in SMEs by Alkhoraif et al. (2019) showed that multiple case studies and mixed-methods only consisted of 11% and 7%, respectively, as compared to the single case study (34%) and survey (30%). Osman et al. (2020) presented that most literature on LM research in Malaysia were empirical articles, mostly with survey studies (42%) as compared to mixed methods (2%). Therefore, convergent parallel mixed-methods (qualitative and quantitative) research was employed in the case of the three M&E companies to provide a comprehensive analysis of the research problems and increase the accuracy of the results. The qualitative study was carried out by using the semi-structured open-ended interview. Ainul Azyan et al. (2017) developed the interview questionnaires to identify success factors and barriers faced in implementing lean in the printing industry. The respondents in the case study were asked about their barriers faced in the LM implementation and CSFs in a structured manner. The interview questionnaires were revised and adapted from Ainul Azyan et al. (2017) to match the purpose of this study.

The interview questionnaires were divided into two sections:

- the general company background and the respondent's profile;
- the predominant lean CSFs and barriers.

All companies were notified at least three weeks in advance before the visit. The interview protocol was emailed to them for reference preparation. Prior to interviews, the questionnaires were verified by two local university lecturers who are experts in the best practice of LM and manufacturing. This was done to confirm that the SME respondents would understand the meaning of the questions and ensure the reliability of the obtained results. Each analysed company was represented by three employees (Table 3) selected from the management level to participate in the face-to-face interview in their premises. This was done to ensure the insight could be more comprehensive and generalise from different levels of the organisations.

Each interview session was conducted within one to two hours on different days due to a tight schedule and completed in around 3.5 months. The respondents were initially briefed about the interview protocol and were also provided with a copy of the questionnaire for reference. The interviews were audio-recorded and transcribed during data collection for analysis with the permission of the respondents. A total of 40 targeted case respondents were chosen to answer the quantitative survey from executive-level staff in the first visit. In the survey questionnaires, there were a total of four closed-ended 5-point Likert questions. The respondents were asked to rate answers to the questions (variables) by measuring their agreement using values ranging between 1 (lowest) and 5 (highest). Additionally, the manufacturing process on the production floor was observed. Site plant tours were also arranged for verification of responses from respondents as well as for the overall picture of the work environment and operation systems.

3. Research results

Company A has been mainly producing rubber machinery since 1990. It provides the design and installation of natural rubber processing machinery according to customer needs, primarily focusing on automation. This has dramatically reduced labour demand and improved productivity. Basic 5S and visual display have been implemented in the company, but the result was considered far from the expectation. Middle management responded that the shop floor operators were not familiar with the LM philosophy and did not possess the relevant know-how and skills to execute the lean application. For example, the production line leader and shop floor employees still did not know how to initiate the lean

Tab. 2. Profile information of companies included in the study

Company name	A	B	C
Establishment year	1990	2006	1997
Company ownership	Family own	Joint venture	Joint venture
No. of full-time employees	32	60	40
Year sales turnover (RM)	Within a range of 5–10 million	Within a range of 5–10 million	Within a range of 10–15 million
Main products	Rubbery machinery	Surface treatment	Industrial wires
Certifications/achievements	Achieved SMEs SCORE 4 star (2019)	ISO 9001:2015; AS9001; NADCAP; SME Award 2015	ISO 9001:2015; ISO 14001:2015
No. of years of the LM implementation	≈3 years	≈7 years	≈15 years
Production type	High mix low volume	High mix low volume	Low mix high volume
Type of an M&E sub-sector	General industrial M&E parts	Specialised process in M&E agriculture	Specialised process in M&E aerospace

Tab. 3. Designation and management level of interviewed respondents

Company/respondents	A	B	C
Senior management	Senior engineering manager	Senior factory manager	General manager
Middle management	Research & development manager	Planner	Business manager
Lower management	Finance executive	Quality engineer	Quality executive

implementation, project selection, who was the primary responsible person to be involved and so on. The lower management revealed that there was no regular daily production meeting conducted which consisted of the management level staff and shop floor employees to discuss the problems faced during the LM implementation and communicate their opinions for solutions. There was a lack of lean strategic planning and policy enforcement from the senior management level in overseeing the LM implementation. The critical challenges faced by the company during the 5S programme implementation came from the employee attitude and the lack of a lean mindset from the middle management's perspective. The shop floor employees mainly intended to complete the work within the scope of their responsibility, therefore neglecting the LM implementation. Resistance to change by employees caused the lean initiative to fail prematurely. Middle management revealed that the lack of employee motivation and self-initiative to involve in the lean project entailed inconsistent results. For instance, the production technicians were still unable to perform their job satisfactorily if the intention of LM was ignored. Lean projects were deployed ad-hoc by taking short-term measures whenever production problem emerged and always caught into the fire-fighting mode. This often inadvertently led to the creation of other wastes. For example, 5S was implemented since 2018 in the equipment store, which resulted in the significant waiting time during operation by maintenance employees rummaging for tools. However, continuous improvement mechanisms and leader standard work were not in place to regulate the 5S system. Most of the shop floor employees practised the basic 5S, especially in the first 3S: Sort, Set in Order and Shine without a deep understanding of the lean concept purposes. The most important of the last "2S" in 5S — Standardise and Sustain — were not adequately followed up with consistent execution during the lean implementation due to the lack of persistent and low commitment to seek continuous improvement. Senior management highlighted that there was an urgent need to have the systematic LM implementation strategy framework in-place and initiate formal intensive 5S training to involve all the employees. Only very few job training sessions were related to LM previously; therefore, senior management feedback that lean training was vital to upgrade the employee knowledge towards the build-up of the lean thinking mindset and application in the workplace. LM projects are usually initiated using the top-down approach from senior management. Middle management leads the lean project as assigned, and then lower management works with the shop floor employees in execution parts based on the given instructions. There is no specific step-by-step process framework planning to follow for the lean project implementation. There is no synchronisation in the common objectives between the management and the shop floor employees, and this caused the lean results to end up not able to meet the expected outcomes. While the LM implementation was sparse in the company A, the top management hoped the concept could bring positive transformation to productivity, working culture and skill competency. The company strategy clearly outlined the plan to strengthen the lean foundation, followed by the incorporation of automation.

Company B is a total solution with a full-service custom metal finishing company with many years of experience in the surface treatment industry. The company specialises in surface finishing for aluminium and anodising of aluminium alloys and other ferrous or non-ferrous electroplating. It owns a land plot of 72 000 square feet with a wide range of process capabilities for various industries, including the aerospace sector. The operating level staff, mostly fresh to the lean concept, naturally required more time to acquire the knowledge. The implemented lean tools include kaizen, Gemba, one-point lesson (OPL), 5S, visual control, standard operation procedure (SOP), and statistical process control (SPC). Company B started LM on a small scale and gradually expanded the proven practice across the plant. Top management showed excellent leadership by introducing many new LM ideas sourced from external parties, such as competitors and customers. The factory manager oversaw the entire LM implementation, and the LM project was led by the respective managerial level staff with cross-functional team collaboration between each relevant department. The lean project management included planning the required timeline and resources for implementation. The company B would typically use the current resources in LM implementation unless the lean project was justifiable for the return of investment (ROI), and this was also subject to the approval of the top management. It actively identified the opportunity for improvement through the lean foundation established many years ago. For example, the SPC was implemented in 2014, which was incorporated with the process automation at the in-house testing laboratory to monitor the chemical process mixture and concentration-related parameters. Besides, shop floor operators also monitored the trend performance of daily critical process yields using the online SPC chart, and the technician performed troubleshooting whenever the machine detected any abnormality. The top management reviewed the progress of lean projects and discussed the next stage of action. The top management was always open to employees for discussion, and any good suggestions or ideas were appreciated. The middle management highlighted that the employees were practising the new knowledge by applying it in their work independently, following the step-by-step guidance from experienced senior staff. Job rotation was applied as an opportunity to improve the lean knowledge skills of employees and to ensure their self-development. High involvement of employees and the achieved results in the LM implementation improvement projects were also related to the assessment criterion of key performance indicators. The latest challenges faced by the company were lean sustainability and transformation at the juncture of Industrial Revolution 4.0 and smart manufacturing. They looked for highly skilled employees with adequate lean knowledge to manage advanced manufacturing technology and machine digitisation. Barriers faced by the management were human-related, by and large. Low-level shop floor staff resisted lean practices and often made avoidable mistakes. Comprehensive lean training and coaching programs in OPL and SOP were conducted periodically by internal trainers. Besides, lean projects and employee contributions were monitored closely. The management demonstrated its commitment by regularly reviewing lean status and clarified strategy of execution to employees. The prevalence of LM in the organisation was mostly constrained to certain production areas. LM was driven by organisational key performance indicators (KPI), assessed through quantifiable data.

Company C was established in the year 1997 to manufacture industrial wire. It has a good set up of M&E, which provides the advantage of producing the wire as specified by the customers with a different type of imported machines. Company C exports the wire to more than ten countries in the world with a guarantee for the quality, quantity, and the service. The lower management highlighted that lean knowledge of the shop floor operators was relatively shallow during the recruitment as most of them were foreigners with language barriers and diverse educational backgrounds. The higher-level operational staff, such as executives, also lacked a more in-depth lean concept to complete their jobs effectively. For example, the engineers faced difficulties in specifying the value stream of the wire winding process mapping to create a smooth flow. Each employee had strengths in their field of expertise but no lean-specific knowledge. The right selection of lean tools is essential for problem-solving and the cost of quality improvement. Lean tools and practices adopted by the company were kaizen, Gemba, 5S, visual display, SOP and work instruction as part of their ISO management system requirements. Company C started the LM implementation in 2004, in tandem with their pursuit of certification for the ISO 9001 quality management system. The defect of products was the primary form of wastes to influence the lean project selection. Major defective products, such as rejects due to wire entanglement, would be returned to the company by the customer for sorting and rework, and this caused considerable productivity loss and cost of quality. The company lacked experienced lean personnel to train the workers internally in lean-related skills. The training was conducted in response to the critical quality issues on hand, with an emphasis on lean awareness and preventive measures. Internal meetings were called to discuss the non-conformance issues and brainstorm for practical solutions. The supervisor communicated the steps-by-steps guidance to the relevant operators by following the SOP documents with practical demonstration until there was clear understanding. The SOP was in place to ensure the prescribed steps were followed during operation. The senior management showed excellent leadership by allocating the necessary resources, such as finance, time, workforce, and facility for the LM implementation. The LM implementation was led by middle management with the relevant executive staff to monitor the implemented system. A lean committee was formed to plan the LM implementation and assess the risks before seeking the approval of the top management to release. The lean status was reviewed by the senior management as a key decision-maker to make the final call, and the approved procedures were documented. Despite promising results in the lean implementation, standardisations of the lean management system were limited. Some shop floor employees thought that lean was not needed for them, and they did not pay much attention to lean due to the tight production schedule. Employees were likely to revert to old habits due to the lack of motivation, resulting in an eventual setback of the initiative. The top management addressed the challenge by sustaining the LM working culture. Shop floor employees needed to be continuously reminded of performing the work following the SOP properly and creating lean initiatives to resolve problems. The middle management underlined the importance for managers to lead by example in the LM implementation aiming to cultivate teamwork and positive change in the working culture. The senior management believed that the encouragement, motivation, performance review with rewards, training and communication could improve employee capability to perform their jobs. The senior management also underlined the integration of the lean management system into daily work to effectively deal with production problems and add value to customers. Aiming to gauge the success of the LM implementation, CSFs highly depend on strong employee teamwork and high involvement, integration of a lean thinking mindset into the working environment as well as following the SOP aligned with the system requirement and outline of the LM implementation framework. The management team was very committed to achieving lean success through workforce skill transformation in alignment with the company strategy to get customer recognition. As quoted from senior management: "Lean is the backbone for the company, which must always underlie and be in line with the daily jobs in the business management".

The hypothesis testing was undertaken to determine whether the outcomes of these four predominant CSFs from the literature review were essential in contributing to the implementation of LM for the analysed SMEs.

Null hypothesis: There are no significant differences for CSFs on the importance level in the LM implementation.

Research hypothesis: There are significant differences of CSFs on the importance level in the LM implementation.

Conducting the Kruskal–Wallis test on independent samples, the tested significance level was at 0.589, which is more than the chosen p-value at 0.05. Therefore, the null hypothesis was retained, and the result showed that there were no significant differences for all four CSFs on the critical level in the LM implementation. The distribution of the significance level was the same across all categories of these factors. The mean ranked values showed that in the population where the sample was drawn, training (86.61) was the most important factor, followed by the leadership and commitment of the top management (83.46). These findings were aligned, indicating that the commitment of the top management and employee involvement were crucial factors and, therefore, they must be embedded during lean implementation process steps (Belhadi et al., 2017; Jani & Desai, 2016). Meanwhile, the LM implementation framework development specifically designed for SMEs, and employee involvement and empowerment had comparable scores with means between 76.49 and 75.44, respectively. In short, all these four identified predominant CSFs showed the importance and had a significant impact on lean adoption in SMEs, as shown in Fig. 1.

Kruskal-Wallis Test

Ranks

	Factors	N	Mean Rank
Important	Top management leadership commitment	40	83.46
	Training education (skill expertises)	40	86.61
	Employee involvement and empowerment	40	75.44
	Lean manufacturing implementation framework	40	76.49
	Total	160	

Test Statistics[a,b]

	Important
Chi-Square	1.919
df	3
Asymp. Sig.	.589

a. Kruskal Wallis Test

b. Grouping Variable: Factors

Fig. 1. Kruskal–Wallis test for predominant CSFs on importance of the LM implementation

4. Discussion of the results

Soft lean practices (human-related aspects) are essential to SMEs (Mamat et al., 2015) and they encompass human resource management, employee motivation, lean training, ethics and professionalism (Abu et al., 2019; Antosz & Stadnicka, 2017; Nordin et al., 2013). Even with an adequate provision of training, SMEs were often unable to deliver the result in LM fully. Staff must practise the learned skills on time, to reinforce and enhance their understanding of LM as a part of a knowledge retention strategy. SMEs find themselves overambitious to embrace lean principles all at once (Grigg et al., 2018; Rose et al., 2017). Employees appreciate lean practice more when it is linked to their daily tasks and convincingly make them easier. The studied SMEs emphasised the critical defect waste of the product as one of the major focus areas in lean project prioritisation. SMEs have a high concern that a customer complaint regarding rejected products that do not meet the requirements would directly affect customer satisfaction and cause long-term business market loss. Returned defective products require rework or end up as scrap, increasing the cost of quality and impacting the production efficiency. SMEs could not afford to have significant financial losses. LM was not widespread but rather restricted to specific areas of the company. The phenomenon was typical to SMEs having a more immediate concern with the constraint of the resource.

Ultimately, sustaining LM aims to realise the lean culture in the organisation (Caldera et al., 2019). Rose et al. (2013) showed the prevalence of 5S, standardisation and kaizen among SMEs operating in the Malaysian industry of automotive components. Similar undertakings were observed in these case studies. Kaizen has been implemented as the team-based collective initiative and strategic management towards the incremental improvement in the critical manufacturing processes of the SMEs. Simple visual management tools, such as display board and signboard, were used as an effective communication tool to convey quick and clear messages to the employees SMEs. The management staff of analysed SMEs were willing to have Gemba walk with the employees to have a first-hand understanding of the real issues occurring on the production floor and immediately discuss the next action plans to solve the problems. This was aligned with the SME characteristics, in which the simple system structure allowed faster communication and facilitated quick decision-making in the LM implementation process (Yusof & Aspinwall, 2000). SMEs preferred lean practices with the least financial investment and fundamental to LM (Rose et al., 2011). However, many small firms lack knowledge regarding lean methods (Matt & Rauch, 2013). For example, the analysed SMEs perceived that lean practices were applied in the organisations, but they were still unfamiliar with the actual lean terminology and lean principles. This conclusion aligns with the findings by Ulewicz & Kučęba (2016), who stated that a major challenge was the lack of knowledge of the techniques and tools used in lean. The intermediate or advanced lean tools, such as small lot sizes, continuous flow, value stream mapping and so on, which are already used by large companies, are still ineffectively introduced into the SME production systems. No specific framework or roadmap exists to guide the analysed companies in the LM implementation. They implement lean tools using different methodologies and unsystematically. Regardless of the perceived level of understanding in LM, SMEs often failed to demonstrate the concept during actual implementation (Kherbach et al., 2019). Wong & Wong (2011b) stressed the prerequisite for an organisation to have its staff adequately immersed in lean thinking and acting to succeed in the lean initiative. Shop floor employees should always transfer lean knowledge into the know-how practice ("act lean"). The primary barrier to lean adoption is the worker attitude or their resistance to change (Chan et al., 2019). An employee should have a positive attitude towards the adoption of LM, in addition to the nurtured desire for a continuous improvement. The case studies of SMEs explored the perception of the determinant CSFs from the interviewee's perspective (Table 4). The rank order was determined based on how many times a critical success factor was referred to during the interview sessions and highly stressed by the interviewees. The categorisation of each level was indicated as H — High, M — Medium, and L — Low.

The leadership and commitment of the top management are pivotal in LM (Gandhi et al., 2018), as well as training and encouragement of employees. The top management supports a lean management system, restructures organisation accordingly, sets the strategic direction, and communicates the lean policy effectively to all employees. The top management must lead by example and render unwavering support (and resource allocation) to lean initiatives. The top management should act as a "change agent" in the company and convince others of the lean ben-

Tab. 4. SME perception of the determinant CSFs

Company name/SME perception of the determinant CSFs	A	B	C
Lean knowledge and experiences of the managers	L	M	M
Leadership and commitment of the top management	H	H	H
Resource capability (financial, time, workforce)	H	H	H
Change in the organisational culture	H	H	H
Understanding of lean tools, employee knowledge	H	H	H
Employee involvement, empowerment	H	H	H
External support from consultants	L	L	L
Training, education and skills	H	H	H
Effective communication	M	M	H
Customer focus	H	H	H
LM implementation strategy plan, goal, vision	H	H	H
Performance management system	L	H	M
Technology resource	L	M	L
Government intervention	H	M	M
Supplier management	L	M	M
Project management and planning	M	M	H

efits. It is essential for companies to identify a motivated "change agent" who can serve as a catalyst for change (Dora et al., 2016). This includes empowering employees by giving them responsibility for the LM implementation. All respondents of the analysed companies were in high agreement that the leadership and commitment of the top management were the primary determinants for the success of the LM implementation in their companies. To quote the quality executive from company C: "The top management will provide the strategic direction, advise and resource commitment (including financial support for training and facilities) to staff in the LM implementation".

The voice of customers was emphasised by the analysed companies as critical. It is the key determinant of the business market growth, which places it in the centre of attention. Indeed, LM aims to create value-added products or services for customers that they are willing to pay for. In contrast, this finding is opposite to the conclusion by Belhadi et al. (2019), who started the priority list with the lowest critical success factor "market, customers and suppliers". One of the advantages of SMEs is their better understanding of customer needs and the ability to respond quickly to immediate customer feedback (Yusof & Aspinwall, 2000). York & Danes (2014) presented a review of the customer development model for entrepreneurial activities to improve decision-making within the lean startup for new product development. According to the business marketing manager in company C: "The motivation of lean adoption is to satisfy the customer's requirements and to get their recognition. It will be more advantageous for SMEs to survive in the global business market competition if SMEs are able to adopt the lean idea recommended or specially required by the customers. The customer's valuable feedback at the early new product development stage is essential for the continuous internal lean improvement in achieving the smooth run of the mass production later".

Resource capabilities, such as finance, time and workforce, are instrumental for SMEs in the LM implementation. SMEs often face the capabilities of the resources due to cash flow issues and high operating costs. Therefore, SMEs should utilise the resources wisely and effectively, with the measurable return of investment. Financial inadequacy is a major challenge in lean adoption and affects the implementation of LM within SMEs (Achanga et al., 2006). For example, neither of the three SMEs hire lean consultants to conducted training for the guided implementation due to the lack of urgency. SMEs focused on settling the major issues faced on the production shop floor first, which were already known to them before they need to consider hiring a consultant. A quality engineer in company B said: "Due to the low workload and small capacity in SMEs compared with other large organisations, it is not justifiable to allocate the budget for hiring a lean consultant to be fully and only in-charge of the lean project". The lack of low-level operators is the constraint for SMEs due to high overhead fees for foreign workers and the high turnover rate for the contract workers. This hinders the progress of the LM implementation in SMEs due to the shortage of the workforce. Lean project planning is essential to avoid any disruption to the shop floor during the implementation, especially the time when SMEs need to meet the production deadline. As a senior factory manager from company B said: "We have to slow down the productivity and arranged extra workforce and overtime to ensure the shop floor employees can attend the lean training. Meanwhile, the company must plan wisely in annual budgeting to purchase the upgrade of automation equipment for the lean integrated system in SPC and so on, to optimise the labour force utilisation and improve productivity".

High-performing companies are those with a sustainable lean culture and proactive improvement (Achanga et al., 2006). SMEs should always promote communication with all levels of employees regarding the critical need for early lean transformation. The drastic method is least preferred at the initial stage, as the employee resistance to change easily offsets any effort. Lean culture needs stimulation from the lean-minded leadership; therefore, companies should coach their leader at any level to support the lean culture (Azuan et al., 2017). One of the characteristics for SMEs is the corporate mindset, which is conducive for new change initiatives and behaviour of employees as influenced by the owner or manager (Yusof & Aspinwall, 2000). SMEs can be relatively flexible in their operations compared to large companies (Majava & Ojanperä, 2017). Therefore, the top management of SMEs can adopt the flexibility in the lean change management system to motivate positive thinking among the employees and cultivate the high awareness towards the readiness for the lean implementation. The general manager from company C claimed that: "Flexible change management system should be more practically adapted to suit the need for organisational culture and the situational level to facilitate the lean transformation".

Most SMEs employ people with relatively low skills and do not foster the ideology of skill enhancement (Achanga et al., 2006). Language barriers faced, especially of foreign workers, can be solved via effective communication by using simple words translation and visual aid tools, such as videos to increase their understanding. Although most shop-floor staff members saw the lean benefits, there was still a general lack of lean knowledge among them (Grigg et al., 2018). For example, company A highlighted that it was hard to recruit qualified staff, as graduates of polytechnic schools were insufficiently competent to perform the hands-on lean tasks such as preventive maintenance. There is a visible gap between the skills acquired through formal learning in connection with the industrial applications. Small enterprises should work with the public and private associations on an integrated know-how transfer through cross-collaboration such as training, further education, internship, consulting service and coaching to close the gaps (Matt & Rauch, 2013). Company C also engaged internship students and assigned them with some lean projects especially in machine utilisation during the industrial training period, as the management wanted to know the perspective of outsiders regarding the possibility to expedite the improvement. The teamwork between the internship students and the shop floor employees in a small group can enhance their lean skills through the exchange of in-depth knowledge. Lean knowledge transfer in SMEs is significant for ensuring the success of lean management implementation (Mohd Zahari, 2019). SMEs should train their employees to become experts on the lean subject matter and act as drivers to propagate lean knowledge to others within the organisation. The selected lean trainer should be certified in lean expertise areas and use the opportunity to become a lean coordinator by expanding the knowledge. SMEs also optimise the training fund in tax rebates from government agencies, such as the Human Resources Development Fund (HRDM), to send their employees to external training courses. As a senior engineering manager from company A said: "The technical application knowledge in lean projects can be enhanced with the training grant support from the government sectors and through cross-collaboration with the higher learning institution in terms of knowledge exchange or sharing of lean experiences". The lack of expertise observed in SMEs produces the main conflict with the LM management principles (Moeuf et al., 2016). Shop floor employees could build strong lean knowledge, including technical know-how through intensive training. A finance executive from company A mentioned that: "The majority of the production workers in the company are low-skilled and come from different industries. Extensive internal lean training is essential for upgrading their expertise to handle the job independently". The fundamental training on lean philosophy must be conducted to stimulate the lean awareness ("think lean") of employees during the pre-implementation stage and make them practice the lean principles through "act lean" in their workplaces. SMEs must be proactive in conducting the training which concentrates on early detection approaches and adopts preventive measures on the production quality issues. SMEs must develop a comprehensive lean training plan for staff which covers introduction courses during job orientation, training matrix, regular training program and a formal training assessment method. Employee training should be incorporated into promotion criteria.

The involvement of people is a crucial element in the LM implementation. However, some employees have a misunderstanding of the lean concept and think that lean is unnecessary for them. Thus, SMEs should convince their employees to believe that lean change is required, and it can improve their working aspects. Employees should be given enough lean concept training first at the initial stage before they practically apply the lean tools directly at their workplaces. Some employees have a negative perception that LM brings an extra burden to their current workload. The management should explain the objectives and advantages of lean to let the employees feel and view the dominant effect on lean. Lean involves teamwork support and responsible commitment of employees towards the common goals. The lower management staff who are the connection bridge to the shop floor employees must buy-in the lean initiatives and promote the improvements to others. This fosters the acceptance and participation of shop floor employees in lean adoption. Roslin et al. (2019) suggested that an organisation could build trust and mutual interest to increase employee involvement and empowerment. A good start for lean implementation with excellent results can change the employee mindset and give the momentum to move forward. Lean is not about a quick fix to problems; it needs a desire for continuous improvement from employees. To quote a research & development manager from company A: "One of the factors for the lack of shop floor employee involvement in lean is their lack of confidence in lean. Thus, the company is responsible for understanding employee concerns, motivating them to apply lean practices in their initiatives and acknowledging their efforts".

There is no specific roadmap to implement lean as it needs to be matched with each organisation's culture (Almanei et al., 2017). The critical drivers to enhance the LM adoption are the improvement of shop-floor management, quality management, and manufacturing strategy (Yadav et al., 2019). SMEs need to have a systematic LM implementation framework planning first before actual implementation and ensure that a proper execution by shop-floor employees is managed carefully with right lean tools used to achieve the high quality of lean success at the end. The development of a useful LM implementation framework for SMEs can help them in standardising and sustaining the lean with high efficiencies in waste elimination. Shelleman & Shields (2014) provided an easily feasible and practical framework, by which SMEs can start designing a sustainable development plan to incorporate sustainability considerations. SMEs should explore the right methodology for the LM adoption to suit their business nature and match it with the SMEs characteristic features in terms of their strengths and weaknesses. To quote a planner from company B: "A good LM implementation framework can be used as guideline references for SMEs to plan and follow the important steps through the systematic working instructions formed, and it should be adaptable to suit a different company culture".

Conclusions

There are some difficulties or barriers faced during the implementation, especially human-related issues, such as the adoption of lean understanding knowledge for the enhancement of employee expertise in lean skills, that need to be addressed seriously by the top management. Several predominant CSFs were identified, which impacted the LM implementation in the studied SMEs. M&E manufacturing SMEs must emphasise much on these CSFs during their lean implementation stages to increase the chances of success. The SME management teams have shown a commitment and high interest in the LM implementation in their organisation. M&E manufacturing SMEs firstly need to gain an exceptional understanding of the lean philosophy culture and only then adapt the systematic methodology of the integrated lean management system to suit the company's strategic goals. A comprehensive understanding of these CSFs would help organisations who would like to apply lean principles (Kundu & Murali Manohar, 2012). The level of success of the LM application is mainly dependent on strong support from the top management leadership and active involvement from all levels of employees in SMEs with those necessary lean resources provided, such as extensive training and effective LM framework planning. Lean implementation can be accomplished successfully and efficiently by manufacturing companies if they take commit and spend the necessary resources on the key CSFs (Nguyen & Chinh, 2017). In short, the study achieved the objectives, and the qualitative results (of the interview) were confirmed by the quantitative findings (of the survey) in this convergent parallel mixed-method research.

This research has made three major contributions. First, it was probably the first to explore the details of CSFs, specifically in the M&E manufacturing SMEs. It provides useful references for the LM implementation, which could provide the right direction for M&E manufacturing SMEs as practical guidelines in industrial application. Second, the in-depth interviews and survey covered the holistic perspectives from the lower management to the senior management levels. This shows that the success of the LM implementation is highly dependent on the involvement and commitment of all stakeholders in the company. Third, most of the CSFs for SMEs were matched with findings of the literature review. This study was further extended to the importance of customer focus on business sustainability. This research was limited to the M&E manufacturing SMEs located in the Malacca state of Malaysia, which restricts the generalisation of the findings. Future research is recommended to explore the priority order or criticality levels of the identified predominant success factors in the LM implementation in other manufacturing sectors of different states with large sample size and including the shop floor employees to validate the findings.

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Efficiency of oil-production: the role of institutional factors

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ABSTRACT
The article aims to provide a theoretical basis for the assessment of the institutional impact on oil production. The availability of fuel is the key driver of the functioning national economy, which determines the strategic and tactical landmarks of socio-economic development and vectors of the country's foreign economic course. Such tendencies are represented in the results of the provided correlation analysis of the fluctuation between oil-production volumes and greenhouse gas emissions, the use of alternative energy sources, the number of patents for oil production, and unemployment. The provided bibliometric analysis, which was made using VOSviewer, has shown the content of interconnections between the categories of oil production and institutional determinants. The authors hypothesised that changes in the institutional environment and their interconnectedness formed a chain "oil production and oil rents → the level of corruption → the efficiency of public governance". The hypothesis was confirmed by constructing a system of dynamic models and using the Generalised Method of Moments. The calculations confirmed that oil rents were associated with corruption and were a direct threat to the stability of public institutions. An increasing level of corruption was associated with an increase in the level of rent payments and occurred only when the quality of democratic institutions was below the threshold level. The current level of efficiency in public administration did not have a significant impact on national oil production. Of all indicators, only the level of political stability had a statistically significant impact on oil production. The identified interconnections provide the basis for creating an efficient state policy aimed at effectively functioning state institutions, which promote the development of the oil industry, and the reduction of the country's energy dependence as well as strengthen the resilience of the national economy.

KEY WORDS
oil production, corruption, oil rent, corruption, government

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Introduction

The level of development of the national economy determines the strategic and tactical guidelines for the socio-economic policy of countries, regions, and global organisations. In turn, the economic, social and environmental development depends on many factors, causes and prerequisites.

One of the most critical factors in determining the content of policies is the availability of raw materials and fuel. The contemporary technologically

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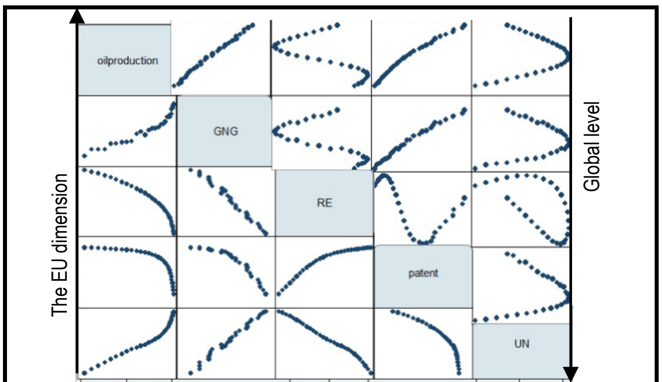
advanced society consumes enormous amounts of energy, which, in turn, raised considerable interest in energy sources. In the structure of global fuel consumption, oil occupies the first place with about 30%, and it is projected to maintain this figure for many years to come (Yevdokimov et al., 2018; Naser, 2019; Miśkiewicz, 2018). Gas and coal lack many useful properties of oil, such as ease of transportation or high heat of combustion (Miśkiewicz, 2020). Thus, having a significant place in the structure of the fuel and energy mix, oil deposits and the scale of oil production are significant determinants, which largely define the content of processes in the economy of individual countries, regions and around the world (Dźwigoł, 2018).

It should be noted that theoretical and applied aspects related to the functioning of the oil industry are widely represented in scientific publications devoted to the study of the main determinants of the industry, the impact of political factors and international oil cartels on the industry, and the analysis of conflicts in oil production. Also, scientists (Kuzior, 2019; Dzwigol, 2020; Czyżewski, 2019) investigated the efficient development of state institutions, which could be realised based on several principles, i.e., the focus on long-term goals of development; equal access to the subsoil; transparency; standardisation of information about resources; stakeholder inclusiveness; systematic approach and complexity; ecological and socio-economic efficiency; consecution; accountability; prevention; adaptability and flexibility of public administration; and the focus on innovation.

The efficiency of the oil production industry is a category connected with the economic, political, institutional, ecologic and social components. However, the influence of institutional factors on the efficiency of the oil industry is still insufficiently studied. So, Fig. 1 shows the results of a correlation analysis into the fluctuation of oil production volumes (for EU countries and the world) and greenhouse gas emissions, the use of alternative energy sources, the number of patents for oil production, and unemployment. The relevant trends are determined by distinguishing the cyclic time-series component by the Godrick–Prescott filter (1), which leads to the conclusion regarding a close correlation between oil extraction and socio-economic parameters of countries.

$$\min_{\tau_t} \sum_{t=1}^{T}((y_t - \tau_t)^2 + \lambda((\tau_{t+1} - \tau_t) - (\tau_t - \tau_{t-1}))^2) \qquad (1)$$

τ_t — trend component, which is determined from the actual data series y_t; y_t — actual data of the value of the j-th element of socio-ecological and economic parameters and volumes of oil production; T = 1…t — the study period.



Pearson Correlation Matrix

	Variables	Global				
		OP	GHG	RE	P	UN
EU	OP	1	0.99*	–0.68*	0.99*	0.26
	GHG	0.97*	1	–0.67*	0.99*	0.22*
	RE	–0.99*	–0.99*	1	–0.59*	–0.58*
	P	–0.84*	–0.94*	0.89*	1	0.11
	UN	0.97*	0.99*	–0.99*	–0.94*	1

Fig. 1. Results of the correlation analysis into the fluctuation between oil production volumes (for EU countries and the world), greenhouse gas emissions, the use of alternative energy sources, the number of patents for oil production and unemployment

Note: OP — volumes of oil production; GHG — greenhouse gas emissions; RE — the share of alternative energy sources; P — number of patents; UN — unemployment rate; * — statistical significance at the level of 1%

For the EU countries and the global dimension, the correlation is close: 97% and 99% between oil production and greenhouse gas emissions; 99% and 68% between the oil extraction and specific use of alternative energy sources; 84% and 99% between the oil production and the number of patents for oil production; and 97% and 26% between the oil production and unemployment. Thus, the development of the oil industry and the decrease in the greenhouse gas emissions could be realised through a greater focus on renewable energy and the implementation of sustainable development principals in the oil industry (Boiko, 2019). In this case, researchers (Cebula et al., 2018; Bhowmik, 2019; Hasan, 2019; He, 2019) proved a positive impact of green investments on declining GHG emissions and increasing share of renewable energy. Several researchers (Vasilieva et al., 2017; Bilan et al., 2018a) also confirmed that government transparency and social policy had a significant impact on the sustainable development of other sectors and investment attractiveness. Besides, a number of studies (Vasylyeva et al., 2014; Lyulyov et al., 2019; Sokolenko et al., 2017; Mentel et al., 2018; Kwilinski, 2019) proved that the modernisation of technologies in the oil industry and the development of green technologies led to a decline in GHG emissions and an increase in GDP.

Meanwhile, the results of studies (Abaas et al., 2018; Bilan et al., 2019b; Pimonenko et al., 2018; Wale-Awe & Sulaiman, 2020) indicate that, in addition to traditional factors, several institutional factors influence the efficiency of the oil industry. A significant impact is made by an intense shadow in the industry, non-transparency of regulatory mechanisms for issuing permits and licenses for production, and corruption in the allocation of quotas for oil production. The goal of the article is to provide a theoretical basis for the assessment of the institutional impact on the oil-production industry.

1. Literature review

The interdependence between the macroeconomic stability and the quality of the institutional environment has been proved by several research efforts (Lyeonov et al., 2019; Bilan et al., 2019a). The main indicators used to measure the quality of public administration have been selected as indicators of the institutional environment. In their paper, Hooke and Yongruck (2019) noted that the effectiveness of state governance affected the competitiveness of countries. Meanwhile, several authors (Chygryn et al., 2018; Kozmenko et al., 2011; Brychko et al., 2019; Grenäākovã, et al., 2019; Marcel, 2019; Augbaka et al., 2019; Pleines et al., 2016) confirmed that the financial stability and an investment climate had an impact on the national stability. Other authors (Bilan et al., 2019a; Vasilyeva, 2019) confirmed the effect of the country's brand and the stability on its competitiveness.

A statistically significant correlation has been found (Sadaf at al., 2018) between the levels of corruption and the effectiveness of governance in the country. A linear regression model has been used to confirm the hypothesis of the study. It has also been found that increased controls on corruption and increased political stability led to a reduction in the number of fraud cases in all sectors of the national economy. Also, the hypothesis regarding a relationship between the effectiveness of governance in the country and inclusive development has been empirically confirmed (Chou, 2018) as well as the growth of corruption under conditions of the shadow economy (Levchenko et al., 2018).

Using the results of panel data analysis, researchers (Awan et al., 2018) concluded that the efficiency of governance and political stability have a positive and statistically significant impact on the economic growth of the country. In addition, corruption has a negative impact on the economic growth of the country, and the effectiveness of governance has the most significant impact on the dynamics of the GDP growth. The Fixed Effects Method and the Hausman test were used to confirm the hypothesis empirically.

The hypothesis of a causal relationship between levels of economic development, corruption, and political instability, as exemplified by West African countries, was empirically confirmed (Nurudeen et al., 2015) with the help of the Granger test and the method of error correction. The results indicated a positive unidirectional dependence of political instability on economic development in the short term and a positive unidirectional dependence of political instability on economic development as well as long-term corruption in West African countries. A statistically significant impact of the level of corruption and the effectiveness of government on the country's competitiveness has been highlighted in the study by Cheng et al. (2017). Huque (2019) confirmed the hypothesis that freedom, voice and accountability affect the country's development.

The impact of corruption in the oil and gas sector on the country's economic growth rate has been addressed by Donwa et al. (2015). Pleines et al. (2016)

examined the example of Caspian oil and gas and concluded that the internationalisation of corruption negatively impacted the development of the oil and gas sector. In the Caspian countries, the oil and gas industry was found to be a key element of their competitiveness; thus, it was crucial to increase the efficiency and quality of government regulation in order to reduce corruption.

To understand the content of interconnections between the categories of oil production and institutional determinants, a bibliometric analysis was performed to determine the spread of the categories. Articles indexed in the Scopus base were selected for analysis.

Scopus analysis tools were used to review more than 15000 papers announced in 1990–2018 (Fig. 2).

The Scopus screening tools showed 1995 as the year for the start of the growth in the number of articles regarding the influence made by the institutional environment on the oil industry. 2018 already saw about 15000 articles, which is an increase of approx. 15 times compared to 1995 (Fig. 2). The relevance of the problems and scientific interest connected with inequalities in the oil extraction countries is continuously growing.

The main subject areas (Fig. 3) related to the marketing strategies are energy, earth and planet science, engineering, chemical engineering, environmental science, business, management and accounting, chemistry, social science etc.

The citation analysis, provided by VOSviewer (Halicka, 2017; Gudanowska, 2017; Siderska & Jadaa, 2018; Winkowska et al., 2019) determined the most authoritative researchers as well as the nine clusters of research teams that had the most significant influence on the theory which describes the interconnections between oil production tendencies and the institutional environment in national economies (Fig. 4). The cluster connected with corruption includes such categories as governance, property rights, economic

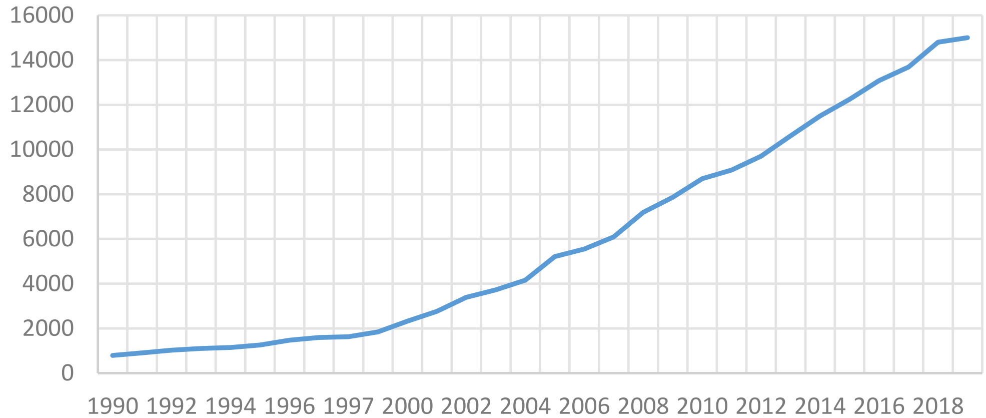


Fig. 2. Results of the trend analysis in publications related to oil production and institutional environment
Sources: elaborated by the authors based on Scopus.

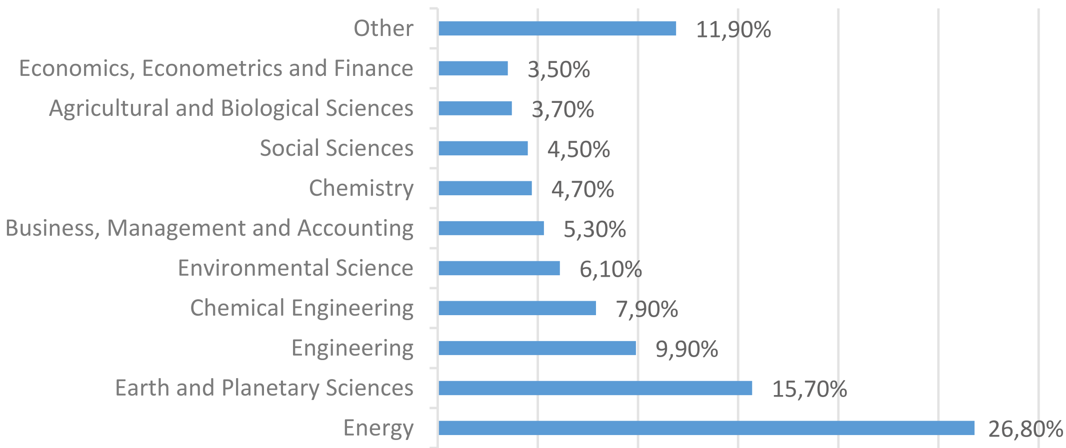


Fig. 3. Subject areas in Scopus dealing with the oil industry and institutional environment
Source: elaborated by the authors based on Scopus.

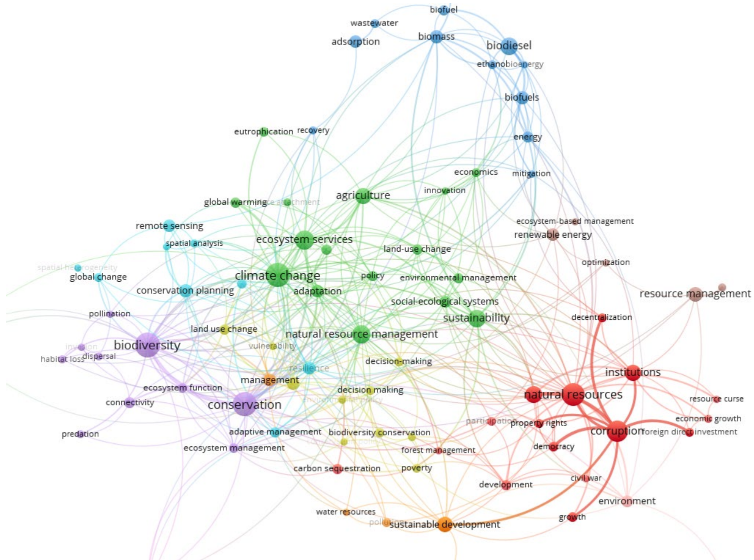


Fig. 4. Results of bibliometric analysis of the structural and functional environment for categories of the oil industry and institutional environment

Source: elaborated by the authors based on Scopus.

growth etc. Another big cluster relates to categories of conservation, biodiversity, and climate change. That explains the influence of the oil industry on the natural environment.

Considering the above-mentioned results of the analysis, this paper hypothesised that changes in the institutional environment and their interconnectedness occurred in the form of a chain, namely, "oil production and oil rents → the level of corruption → the efficiency of public governance".

2. Research methods

Assessment of the interconnection between the institutional environment and oil production, oil rents, the level of corruption and the efficiency of public governance could be conducted based on the dynamic models and using the Generalised Method of Moments (GMM), proposed by Arellano–Bond (1991):

$$\Delta Y_{i,t} = \alpha_i \Delta Y_{i,t-1} + \beta_i \Delta X_{i,t} + \Delta\varepsilon_{i,t} \qquad (2)$$

where Y_{it} — the dependent variable, $X_{i,t}$ — vector of explanatory variables, α, β, and λ — parameters to be estimated; ε_{it} — statistical error; Δ — the first difference sign; and i and t represent country and time, respectively.

Based on the above, the empirical model (3–5) can be represented as:

$$\Delta OP_{i,t} = \alpha_1 \Delta OP_{i,t-1} + \zeta_1 \Delta Corruption_{i,t} + \zeta_{2i} \Delta Z_{it} + \Delta\varepsilon_{i,t} \qquad (3)$$

$$\Delta Corruption_{i,t} = \alpha_2 \Delta Corruption_{i,t-1} + \zeta_3 \Delta OP_{i,t} + {} + \zeta_4 \Delta Z_{i,t} + \Delta\varepsilon_{i,t} \qquad (4)$$

$$\Delta Z_{i,t} = \alpha_3 \Delta Z_{i,t-1} + \zeta_5 \Delta Corruption_{i,t} + \zeta_6 \Delta OP_{i,t} + \Delta\varepsilon_{i,t}, \qquad (5)$$

where $\alpha_1 \ldots \alpha_3$, $\zeta_1 - \zeta_6$ — model constants; $OP_{i,t}$ — indicators of oil industry functioning (OP_1 — the volume of oil production; OP_2 — the volume of rent payments for oil), $Z_{i,t}$— World Governance indicators which represent the quality of governance; $Corruption_{it}$ — the Corruption Perceptions Index according to Transparency International; ε_{it} — statistical error; Δ — the first difference sign; and i and t represent country and time, respectively.

It should be noted that the system of world indicators has already been used (Huque et al., 2018; Chou et al., 2018; Sadaf et al., 2018; Awan et al., 2018; Cheng et al., 2017; Nurudeen et al., 2015; Donwa et al., 2015; Kasztelnik et al., 2019) for measuring public administration quality as an information base for evaluating institutional factors (The Worldwide Governance Indicators (WGI)). It should be noted that these indicators have been calculated for 200 countries since 1996 using more than 30 databases, including survey results. Therefore, this sample is representative of both time and country surveys. According to the officially announced methodology, this metric system contains six aggregating indicators, namely, voting rights and accountability; political stability; the effectiveness of the functioning government; the quality of the government's regulatory policy; the rule of law; and the control of corruption.

Accordingly, the Zi,t indicator in the article is evaluated based on several determinants of the institutional environment, namely, the opinions of the population during the formation of political institutions, political stability, the effectiveness of the government, and the level of adherence to the rule of law in the country. The information base of the study was data from 21 countries for the years 2000–2018.

3. Research results

According to official reports (Kaufmann et al., 2010), countries with high and higher than average incomes rank higher in terms of voting power and accountability. It should be noted that in 2004–2009, there was a positive trend in the growth of the right to vote and accountability. After 2009, the value of this indicator began to decline. The sharp changes in the dynamics of this indicator relate to the existing political and economic conflicts. The dynamics of changing the indicator of voting power and accountability are presented in Fig. 5.

The results of the analysis into the dynamics of the indicator change — the quality of the government's regulatory policy — landed Ukraine in the last position. In terms of this indicator, the position of Ukraine began to decline rapidly after 2004, as with the previous indicator. As of 2004, Ukraine had 39.41 points, and in 2015, it had 29.33 points. It should be noted, that after 2005, the quality of the regulatory policy of the Ukrainian government began to improve, which is confirmed by the growth of the indicator of the quality of the government's regulatory policy in 2018 to 44.23 points.

According to Fig. 6, the lowest positions among the analysed countries during the analysed period of

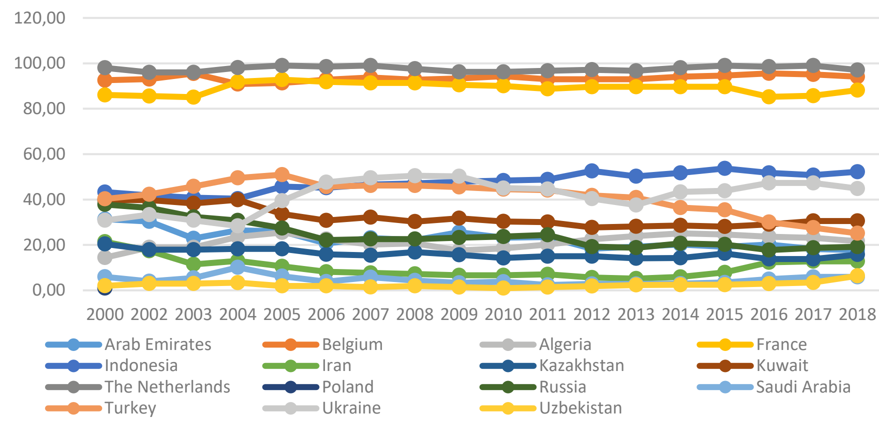


Fig. 5. Dynamics of indicator change: voting rights and accountability in 2000–2018

Source: elaborated by the authors based on (Bilan et al., 2019c).

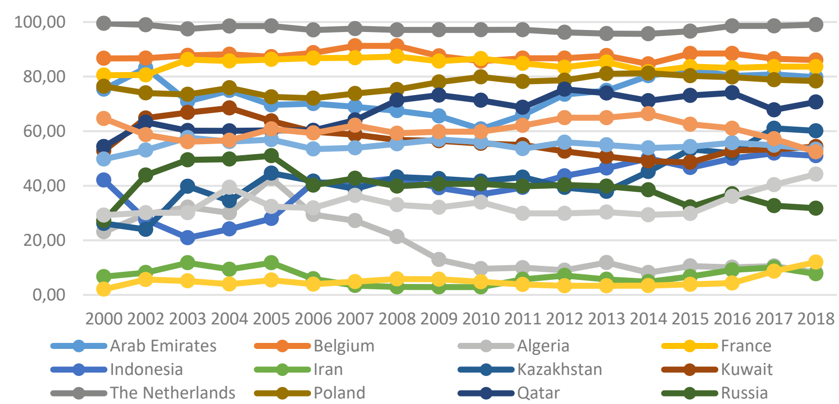


Fig. 6. Dynamics the indicator of the quality of the government's regulatory policy in 2000–2018

Source: elaborated by the authors based on World Governance Indicators.

2000–2018 were held by Iran and Uzbekistan (Kaufmann et al., 2010). As with the previous indicator (voting rights and accountability), the highest positions was held by the Netherlands. It should be noted that in terms of corruption control, Ukraine also ranked last among the analysed countries. As with the previous indicators, the dynamics of the decline was observed after 2005, and the lowest value was found in 2013, which was 11.37 points. In 2016 and 2017, the value of this indicator increased almost twice and amounted to 21.5 and 22.12 points, respectively.

The downward trend is also observed in Kuwait, Turkey, Algeria and Iran. As of 2002, the indicator of the control of corruption for Kuwait was 82.83 points, and in 2017, it was almost twice lower at 44.71 points; in Iran, in 2002, it was 50.0 points, while in 2017, it was 22.12 points. Uzbekistan, Kazakhstan and Russia have similar points to Ukraine for this indicator.

According to the results of the analysis (Fig. 8), Kazakhstan was the leader in all indicators of government efficiency in 2016. Ukraine was ahead of Russia and Uzbekistan in the indicators of the rule of law and the control of corruption.

Russia was in the lead in terms of voting rights and accountability; the efficiency of the functioning government; and the quality of the government's regulatory policy.

In 2016, Uzbekistan achieved better results than Ukraine and Russia in terms of political stability.

Based on the comparison of the values for government performance indicators by Ukraine, Russia, Kazakhstan and Uzbekistan, Kazakhstan ranked first in almost all parameters in 2017. Ukraine had a better-quality regulatory policy, the rule of law and anti-corruption controls than Russia and Uzbekistan. Meanwhile, Russia had almost the same position with Kazakhstan in terms of the efficiency of the functioning government (Fig. 9).

In 2018, Kazakhstan was also the leader in all indicators. Russia was ahead of Ukraine and Uzbekistan in three indicators: the control of corruption; voting rights and accountability; and the efficiency of the functioning government.

Compared to 2016 and 2017, Ukraine's position in terms of the indicator of the control of corruption dropped in 2018; however, the quality of the government's regulatory policy received a better ranking. Fig. 10 presents a graphical interpretation of the effectiveness of the state governance in Ukraine, Russia, Kazakhstan and Uzbekistan for 2018 in terms of main components.

Summarising the results of the analysis into Ukraine's position in terms of indicators of the effectiveness of the government, a conclusion can be drawn that in 2016–2018, only three indicators increased among the six, namely, voting rights and accountability, the effectiveness of the functioning government, and the quality of the government's regulatory policy.

In 2018, there was a slight decrease in indicators of political stability and the rule of law.

At the same time, there was a significant decrease in the indicator of the control of corruption. Fig. 11 presents the dynamics of change in the performance indicators of the state governance in Ukraine for 2016–2018 in terms of major components.

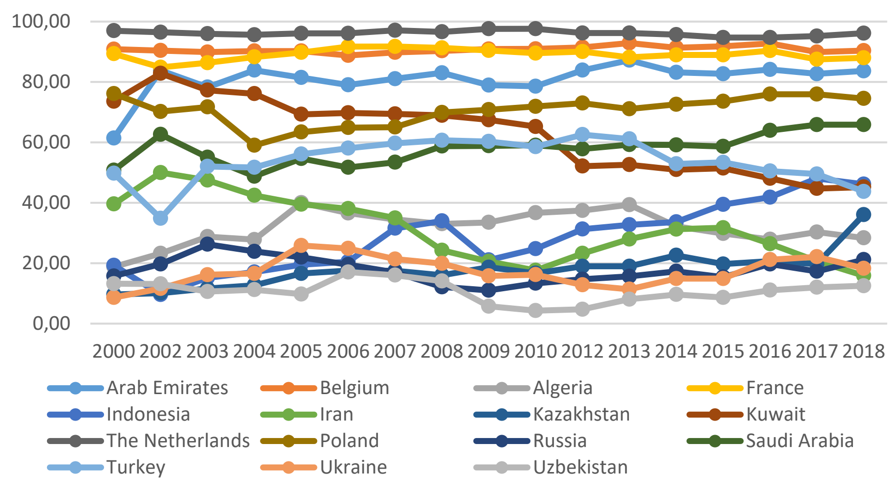


Fig. 7. Dynamics of the indicator or the control of corruption in 2000–2018

Source: elaborated by the authors based on World Governance Indicators.

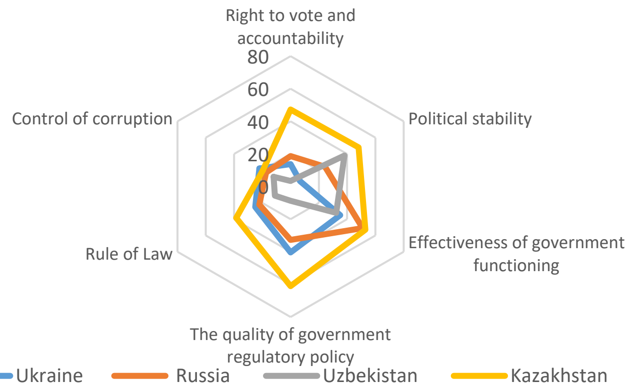


Fig. 8. Public Governance Effectiveness in Ukraine, Russia, Kazakhstan and Uzbekistan in 2016
Source: elaborated by the authors base on World Governance Indicators.

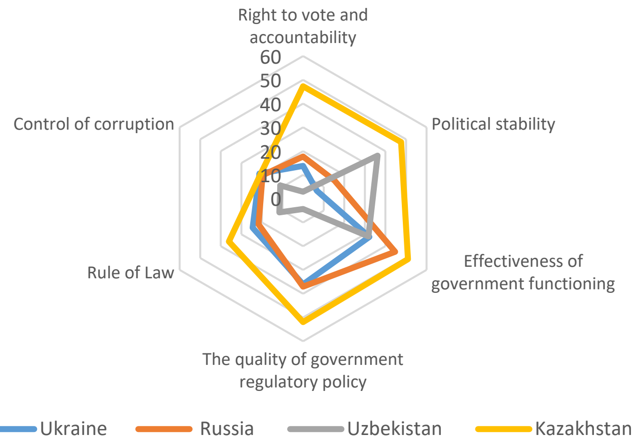


Fig. 9. Efficiency of government in Ukraine, Russia, Kazakhstan and Uzbekistan in 2017
Source: elaborated by the authors base on World Governance Indicators.

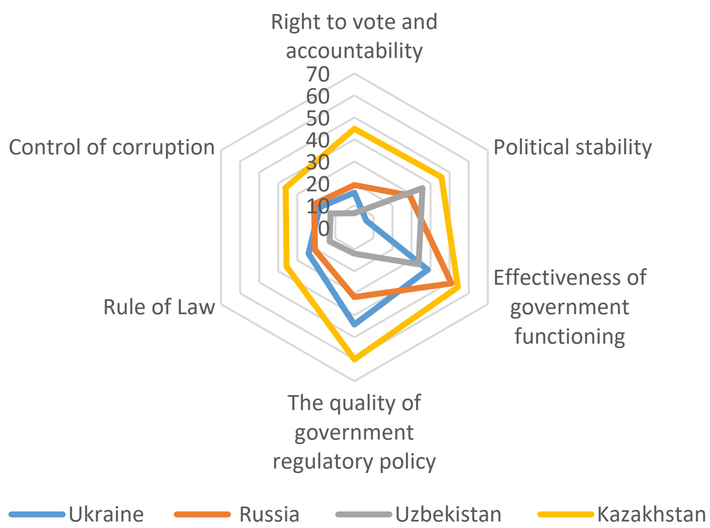


Fig. 10. Public Governance Effectiveness in Ukraine, Russia, Kazakhstan and Uzbekistan in 2018
Source: elaborated by the authors base on World Governance Indicators.

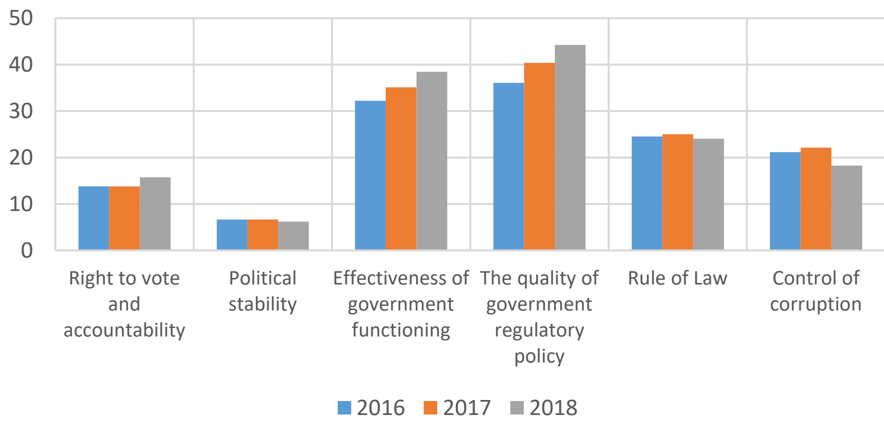


Fig. 11. Dynamics of indicators for the effectiveness of public governance in Ukraine in 2016–2018 by key components

Source: elaborated by the authors base on World Governance Indicators.

The trends represented in Fig. 11 show the tendency for the growth basically in all determinants. A significant increase characterises the effectiveness of the functioning government and the quality of the government's regulatory policy in comparison with political stability.

4. Discussion of the results

The authors of the article calculated the parameters related to the model of interdependence between indicators showing the national development of the institutional environment and the oil production industry (Table 1). The information base consisted of data from 21 countries for 2000–2018. The correlations between the variables in the empirical model (3) are presented in Table 1.

The calculations confirmed that at the present stage of development of the national economy, oil rents are associated with corruption and are a direct threat to the stability of state institutions. Based on Table 1, there is a high correlation between PS and GE, which means that the inclusion of two indicators of the state government performance in the model (3–4) would create a multicollinearity problem. Therefore, the assessment of the impact made by the institutional environment on the functioning of the

Tab. 1. Correlations between variables OP_1, OP_2, ViA, PS, GE, RL

	OP_1	OP_2	ViA	PS	GE	RL
OP_1	1.0000	0.4561 (0.0001)	-0.1593 (0.5147)	0.3484 (0.0000)	-0.3762 (0.1125)	0.0127 (0.9588)
OP_2	0.4561 (0.0001)	1.0000	-0.2110 (0.3859)	0.3476 (0.0002)	-0.4559 (0.0498)	-0.3060 (0.2026)
ViA	-0.1593 (0.5147)	-0.2110 (0.3859)	1.0000	-0.1464 (0.5497)	-0.0138 (0.9552)	0.4578 (0.0487)
PS	0.3484 (0.0000)	0.3476 (0.0002)	-0.1464 (0.5497)	1.0000	-0.644 (0.0029)	-0.1187 (0.6285)
GE	-0.3762 (0.1125)	-0.4559 (0.0498)	-0.0138 (0.9552)	-0.644 (0.0029)	1.0000	0.3326 (0.1641)
RL	0.0127 (0.9588)	-0.3060 (0.2026)	0.4578 (0.0487)	-0.1187 (0.6285)	0.3326 (0.1641)	1.0000

OP_1 — the volume of oil production; OP_2 — the volume of rent payments for oil; ViA — indicator of the opinion of the population during the formation of political institutions; PS — the political stability indicator; GE — governance performance indicator; ΔRL — the rule of law indicator; Corruption —the corruption perception index; in () — the level of significance.

Tab. 2. Results of the study into the impact of the institutional environment on the functioning of the national oil-production industry

	Model specification													
	ΔCorruption		ΔOP_1		ΔOP_2		ΔViA		ΔPS		ΔGE		ΔRL	
	Stat. (Prob.)		Stat. (Prob.)		Stat. (Prob.)		Stat.	Prob.	Stat.	Prob.	Stat.	Prob.	Stat.	Prob.
Corruption	0.12 (0.00)	0.11 (0.00)	–0.16 (0.00)	–0.09 (0.00)	–0.04	0.00	0.04	0.00	–0.03	0.355	0.03	0.00	0.17	0.00
OP_1	1.47 (0.16)	1.34 (0.08)	0.521 (0.00)	0.687 (0.00)	–	–	–0.10	0.14	0.08	0.00	–0.06	0.20	0.06	0.15
OP_2	–0.54 (0.00)	–0.52 (0.00)	–	–	0.490 (0.00)	0.831 (0.00)	–0.98	0.00	0.34	0.72	0.19	0.37	–0.13	0.46
ViA	0.28 (0.00)	0.34 (0.0)	0.30 (0.41)	0.27 (0.44)	0.49 (0.03)	0.64 (0.52)	0.09	0.012	–	–	–	–	–	–
PS	1.25 (0.23)	–	0.23 (0.06)	–	0.13 (0.08)	–	–	–	0.208	0.00	–	–	–	–
GE	–	0.18 (0.00)	–	0.51 (0.18)	–	0.42 (0.06)	–	–	–	–	0.308	0.00	–	–
RL	0.48 (0.92)	0.49 (0.87)	0.32 (0.53)	0.28 (0.48)	–0.15 (0.63)	–0.10 (0.84)	–	–	–	–	–	–	0.07	0.05
AR(2)	(0.209)	(0.312)	(0.311)	(0.291)	(0.243)	(0.218)	(0.149)		(0.178)		(0.269)		(0.117)	
Sargan's OIR stat.	(0.967)	(0.341)	(0.237)	(0.414)	(0.220)	(0.145)	(0.136)		(0.180)		(0.213)		(0.385)	
Hansen's OIR stat.	(0.782)	(0.492)	(0.623)	(0.625)	(0.618)	(0.713)	(0.487)		(1.00)		(0.503)		(0.578)	

AR(2) is the Second-order autocorrelation of residuals; Sargan's OIR stat. and Hansen`s OIR stat. — Sargan and Hansen OIR tests; OIR is the Over-identifying Restrictions Test.

national oil-production industry was made based on the PS and GE indicators separately.

Table 2 represents the results of the study into the impact of the institutional environment on the functioning of the national oil-production industry.

The calculations confirmed (Table 2) that at the current stage of the development of the national economy, oil rents are associated with corruption and are a direct threat to the stability of public institutions. An increase in rents for oil by one point of standard deviation increases the level of corruption by 0.54 points of standard deviation. At the same time, an increase in the level of corruption is associated with an increase in the level of rent payments and occurs only when the quality of democratic institutions is below the threshold level (0.54 standard deviation points). However, the current level of efficiency of public administration does not significantly impact on the national oil-production industry. Of all indicators, only the level of political stability had a statistically significant impact (at 1%) on oil production. Improving political stability by 1.0-point standard deviation will increase oil production by 0.08 standard deviation.

Conclusions

Sustainable development of the oil-production industry should be understood as a process of the capacity building considering the interference of the effects of cross-sectoral interaction. The system of measures for ensuring the sustainable development of oil production has to be aimed at preventing the adverse economic, institutional, social and economic effects of the functioning industry. The analysis made it possible to determine that the development of efficient state institutions will contribute to the development of the oil production industry, will reduce the country's energy dependence and strengthen the stability of the national economy.

To assess the impact of the functioning institutional environment on the development of the national oil industry, the hypothesis was formulated regarding the changes in the institutional environment and their relationships being in the form of the chain "oil production and oil rents → the level of corruption → the efficiency of public administration". To confirm the hypothesis, a scientific and methodological approach was developed, which involved building a system of dynamic models and using a generalised method of moments.

The substantiation of the influence of the institutional environment on the functioning of the national oil production industry showed that the increase in oil rents by one point of standard deviation increased the level of corruption by 0.54 points. The increase in the level of corruption is caused by the increase in the shadow in the oil production industry and occurs when the quality of democratic institutions is below the threshold level. An increase in the level of political stability by one point of standard deviation causes an increase in oil production by 0.08 points of standard deviation.

A proposed theoretical approach for the assessment of the institutional impact on the oil production industry will form the background for the formation of a stimulating institutional environment with the possibility of using appropriate tools for different hierarchical levels of the national economy, creating efficient state policy for the oil-production industry, and developing effective state institutions. It will promote the development of the oil industry and reduce the country's energy dependence and strengthen the resilience of the national economy.

Acknowledgements

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Are smart service manufacturing providers different in cooperation and innovation flexibility, in innovation performance and business performance from non-smart service manufacturing providers?

Lucie Kaňovská

ABSTRACT

To overcome the challenges posed by increasing competition, many traditional manufacturing companies are moving from the mere production of manufacturing goods to the integration of services that are more or less integrated into the product, which is also due to the constant development of the industry. Moreover, many manufacturing companies offer products that use smart technologies. This paper focuses on the importance of smart service provision for cooperation and innovation flexibility, innovation performance and business performance in small and medium manufacturing companies. The paper aims to find out if smart service manufacturing providers are different in cooperation and innovation flexibility and innovation and business performance from non-smart service manufacturing providers. To better understand the issue, research was undertaken in 112 small and medium manufacturing companies of the Czech Republic. The problems of smart service provision were investigated in the first empirical research held among the electric engineering companies (CZ-NACE 26 and CZ-NACE 27) in the Czech Republic. The findings show that smart service manufacturing providers are better in internal cooperation flexibility, innovation flexibility related to product and to accompanying services and in business performance than non-smart service manufacturing providers. Theoretical implication contributes in two specific ways: first, in the presentation of the interconnection of smart services and cooperation flexibility, innovation flexibility, innovation performance and business performance; and second, in the identification of the impact of smart services in manufacturing SMEs and in finding out which areas affect the provision of smart services. The findings can have a positive influence in several areas; therefore, they can be important factors for many manufacturing companies which still need some persuasion to offer smart services.

KEY WORDS

smart services, cooperation flexibility, innovation flexibility, innovation performance, business performance, manufacturing companies

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Introduction

In the last few years, many manufacturing companies have been offering products and related services, including services using smart technologies, which can monitor product operations, inform the customer about their status and transmit this information to manufacturers. The manufacturer can further process this information and use it for monitoring

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the operation of the equipment, remote repair, predictive maintenance or innovation of existing products. Manufacturers financially support digitalisation to reduce data processing costs by automating data collection, warehousing and diagnostics (Wamba et al., 2017). Thanks to these new possibilities, the importance of this area has been growing in recent years.

Despite the rapidly growing development of smart technologies, research in this area in small and medium enterprises (SMEs) is still in its infancy. Smart technologies have great potential; however, their success requires a deep understanding of customer expectations, behaviour and also an understanding of the current situation of manufacturing companies. The fundamental influence of digitisation is often perceived as its influence on companies, up and downstream operations, networks and ecosystem (Porter & Heppelman, 2015). Moreover, digitalisation helps to support new innovative services, business models and pricing models, which are crucial for gaining the value from digitalisation (Kohtamäki et al., 2019).

The issue of accompanying services using smart technology, including the identification of its impact on industrial small and medium-sized enterprises, has not yet received much attention in the Czech Republic, explaining the need for this research. It focused on manufacturing SMEs, which make up the majority of today's businesses and are crucial for the economy. Producers of electric equipment and electronic components from Czech SMEs were respondents in the research. They are essential representatives of the manufacturing industry and subcontractors of many other economic sectors. The growth of Czech exports is also related to the increase in new orders, for which the flexibility of producers and suppliers is necessary.

The competitive advantage of SMEs often lies in the development of specialisation, which allows them to take advantage of greater flexibility in innovation in a changing business environment. Today's businesses are forced to find flexible ways to respond to uncertainty and meet customer demands effectively. This is especially true for SMEs, which often depend on the ability to adapt quickly to the customer. The issue of smart servitisation is specific to SMEs, where the implementation of smart technologies is more demanding due to the often limited financial and personnel capacities. The implementation of digitalisation is challenging for current manufacturing companies. They can invests, but they have problems with creating and appropriating value from these investments (Kohtamäki et al., 2020). Cooperation between companies is becoming increasingly more critical today. The need for resources and capabilities is enormous, and companies hardly manage by themselves, requiring the competencies to manage the ecosystem of suppliers, complementors and stakeholders (Kohtamäki et al., 2019). Likewise, the importance of flexibility is growing, which is increasingly recognised in product innovation as essential for building sustainable competitive advantage.

The current literature either lacks or has limited efforts related to the investigation of the importance of smart services for flexibility in the areas of collaboration, innovation and innovation and business performance. At present, there is no publicly available empirical study on the financial benefits of smart services for electrical engineering companies in the Czech Republic. Even if different companies implemented the same smart services, the benefits would be different for each company, and they would be measured in different parameters depending on the business, business model, management method and current life-cycle stage. Thus, the benefits of smart services can only be measured and demonstrated in a particular company by monitoring the evolution of the parameters that the company wants to improve by implementing smart services.

Therefore, the research also sought to determine how smart services impact the flexibility in cooperation and innovation and the innovation and business performance of industrial SMEs and to try to contribute to a better understanding of the potential benefits of smart services to industrial enterprises. The paper aims to find out if smart service manufacturing providers are different in terms of cooperation and innovation flexibility and innovation and business performance from non-smart service manufacturing providers.

Many authors have focused on smart service offer, their drivers, benefits, including financial, but the view of the impact of smart services on flexibility and performance, even in the field of innovation and cooperation, is a new perspective. The originality of this paper is in another view of smart services, specifically in terms of importance for cooperation and innovation flexibility and for innovation and business performance.

The paper consists of a literature review, methodology, main results, discussions with implications and limitations, and conclusions.

1. Literature review

The subject of the paper is smart services — the area of services that can use smart technologies and are provided to customers of manufacturing companies. Smart services are a special type of service that is provided to a smart object able to perceive its conditions and its surroundings, thus enabling up-to-date data collection, constant communication and interactive feedback (Allmendinger & Lombreglia, 2005). By using smart services, manufacturers can generate additional revenues (Rachinger et al., 2019) and do it so more stably because long-term contracts replace sales (Rymaszewska et al., 2017). Gebauer et al. (2020) attempted to stimulate a further investigation of revenue growth through digitalisation. The use of smart technologies in the provision of services helps companies to reduce the resources used in the provision of services, such as labour costs because fault diagnosis can be performed remotely. Thus, companies can benefit from reduced operating costs (Hasselblatt et al., 2018). In addition, the adoption of smart technology-enabled services can lead to or maintain closer customer relationships because it allows customers to co-create value with the provider, allowing the provider to offer customer-oriented services (Hagberg et al., 2016). In addition, the incorporation of smart technologies makes it possible to expand the portfolio of products and services (Gerpott & May, 2016). As a result, companies will be able to expand their current business (Rymaszewska et al., 2017). Smart technologies can be used to improve the existing range of services because they can be offered in a way that is perceived as more advantageous for the customer. Smart technologies provide insight into product usage behaviour and resource utilisation rates, companies can use this information to improve resource utilisation (Bressanelli et al., 2018). Companies will also gain a competitive advantage from providing services using smart technologies. This is because the fusion of technology and integrated product service offerings is difficult for competitors to imitate (Porter & Heppelmann, 2015). Smart technologies also allow a constant estimate of their current service delivery to identify optimal customer support, which in turn leads to a profitable portfolio of services.

Digital resources can be a lever for innovation in SMEs (Higón, 2012). Also, they change the way we manage innovation (Yoo et al., 2012) and make companies "more extroverted" (Tambe et al., 2012). Digital resources face traditional spatial constraints of companies involved in collaborating for innovation (Deltour et al., 2018). According to Pagani (2013), a growing interest in cooperation between companies can be expected, which will be based on smart services, which change traditional business operations and make cooperation the main factor of success.

Technological innovation requires the growing importance of access to resources outside the enterprise (Gebauer et al., 2013), as the impressive expansion of digital technologies in business puts many enterprises at risk and growing uncertainty (Gimpel & Röglinger, 2015; Siderska, 2020; Sachpazidu-Wójcicka, 2017). The lack of digital capacity, especially in established companies, is the main driving force for companies to decide to introduce collaborative development methods. For this reason, a growing number of multi-organisational collaborations based on smart services can be expected, which change traditional business operations and make collaboration a major success factor (Pagani & Aiello, 2013). It is more frequent for a business customer as well as suppliers, to believe that they will participate in innovation project development, including technological innovation. However, it is a serious topic to gain competitiveness and, more widely, business success for many current businesses (Zadykowicz et al., 2020; Župerkienė et al., 2019; Kohnová et al, 2019). Nowadays, the so-called regional servitisation is becoming a current trend, in which companies in a given locality come together and cooperate on projects together. Through collaboration, manufacturers and intermediaries can help overcome any weaknesses in the capabilities of others to provide comprehensive, advanced services to their customers (Story et al., 2017). Story et al. (2017) illustrate how integration between manufacturers and their intermediaries helps to overcome the limitations of mutual capabilities required for value creation. Companies can improve their financial, market or innovation performance by working with competitors (Le Roy & Czakon, 2016). Surprisingly, however, studies have not yet fully focused on research topics that see a challenge for manufacturers to perceive the importance of networking (Martin et al., 2019).

Pellicelli (2018) noticed that flexibility was more important than ever, as relationships with suppliers were managed through networked companies and multinational global supply chains. Flexibility enables to establish a global supply chain. Di Sivo & Cellucci (2013) stressed that a local supply chain was based on the willingness of all stakeholders to activate virtuous cooperation. Flexibility has become one of the most useful and essential tools in today's competitive markets. Manufacturing flexibility is widely recognised as a critical component for achieving a competitive advantage in the market. Flexibility in product innovation is increasingly recognised as essential for building a sustainable competitive advantage in an increasingly turbulent market (Liao et al., 2010).

2. Research methods

Smart services have "raised high expectations of their potential" (Biehl, 2017) and are widely used to describe a company's innovation. In contrast, the research area of these services is still in its infancy, and it is only in recent years that possible first strategies for their research have emerged (e.g., Wünderlich et al., 2015). Therefore, there is a need for more detailed research to systematise existing knowledge in this area (Grubic & Jennions, 2017).

Nowadays, cooperation between companies is essential as well as innovation and flexibility. As mentioned above, in the field of product innovation, cooperation is increasingly recognised as indispensable for building sustainable competitive advantage. Trying to find out whether companies providing smart services differ in the above areas from companies that do not, can be beneficial for business thinking about the possibility to start or postpone offering smart services.

Therefore, quantitative research also sought to determine how smart services impact cooperation flexibility, innovation flexibility, and the innovation and business performance of manufacturing SMEs, and, thereby, try to contribute to a better understanding of the potential benefits of smart services to manufacturers. This gap is addressed by a research question based on the empirical part of the work.

Research question RQ: Are smart service manufacturing providers different in cooperation and innovation flexibility, in innovation performance and business performance from non-smart service manufacturing providers?

Research question leads to the following hypotheses: H. Cooperation flexibility, innovation flexibility, innovation performance and business performance are higher among smart service manufacturing providers than non-smart smart service manufacturing providers.

To answer the research question and hypotheses, a questionnaire was created to examine the issue of smart services and flexibility and performance in SMEs. The questionnaire contained four main parts: cooperation flexibility (consisting of external cooperation flexibility with customers, external cooperation flexibility with suppliers and internal cooperation flexibility), innovation flexibility (consisting of innovation flexibility related to the product and innovation flexibility related to accompanying services), innovation performance and business performance. The final part of the questionnaire surveyed general information about the respondents, including a query on smart service provision.

Flexibility items were based on Tomášková (2005), Liao & Barnes (2015), Obeidat et al. (2016); innovation performance items — Liao & Barnes (2015) and Obeidat et al. (2016); provision of smart service items — Grubic & Peppard (2016) and Bjerke & Johansson (2015). Three items of business performance measured the use of marketing performance (items 1–3) and two items measured financial performance (items 4–5) based on Grubic & Peppard (2016) and Bjerke and Johansson (2015). The 5-point Likert scale was used in the questionnaire (1 for "No, I don't agree", 5 for "Yes, I agree". For testing all parts of the questionnaire, Cronbach's alpha was used. The levels of reliability for the parts were as follow: external cooperation flexibility for customers (0.792), external cooperation flexibility for suppliers (0.812), internal cooperation flexibility (0.814), innovation flexibility relating to the product (0.832), innovation flexibility relating to accompanying services (0.890), innovation performance (0.677), and business performance (0.673).

Producers of electric equipment and electronic components from Czech SMEs participated in the research. They comply with the Czech industry classification (CZ-NACE 26 — Manufacturer of computer, electronic and optical products and CZ-NACE 27 — The Production of Electrical Equipment). CZ-NACE 26 and CZ-NACE 27 are important representatives of the manufacturing industry and are subcontractors for many other sectors of the economy. In addition, the electrical engineering industry is a global industry, which means that many Czech companies can have customers around the world, but on the other hand, competitors can also be global. Precisely because of the connection of products with digital technologies, electrical engineering companies were chosen, where some manufacturers are already trying to provide services using smart technologies to their products, and customers also perceive their benefits. The growth of Czech exports is also related to the increase in new orders, for which the flexibility of producers and suppliers is necessary. Here, about 70% is generated by the automotive, engineering, electrical and electronics industries. It can be said that high flexibility is one of the most important competitive advantages of many Czech industries (Mařík et al., 2016).

Respondents were mainly managers and directors. They were contacted by email and asked to fill out a web-based questionnaire. The research in SMEs was conducted in July–October 2019. Based on the Czech Statistical Office, the Czech industry classification, CZ-NACE 26 contained 278 companies, and CZ-NACE 27 contained 575 companies with 10–250 employees (data of December 2019). In total, 853 companies were located. Small and medium manufacturers were selected from the Amadeus database. CZ-NACE 26 and CZ-NACE 27 had 730 companies in total, 254 SMEs from CZ-NACE 26 and 476 SMEs from CZ-NACE 27. All of them were addressed by email, but 22 emails were sent back because of their probable exit, liquidation or impossibility to trace them (their contact emails were missing). A total of 112 full-filled questionnaires were obtained, which constitutes a 15.8% rate of return. The software package SPSS, Version 17, was used for data analysis.

In order to fulfil the aim of the paper, a research question and hypothesis were set. The Shapiro–Wilk test, the non-parametric Mann–Whitney U test and the Levene's Test for Equality were used to verify normality.

3. Research results

At the beginning of the description of research results, it is worth mentioning that smart services were provided by 48% of respondents from small businesses and 42% of respondents from medium-sized enterprises. More smart services (48%) were provided by enterprises whose customers were other enterprises (B2B) than enterprises whose customers were final customers (28.6%) (B2C). The most frequently provided smart services included remote monitoring (34%), remote diagnostics (29%), remote repair (23%) and preventive and predictive maintenance (18%).

The processing of research question to distinguish electrotechnical SMEs that provided and did not provide smart services required determination of the hypothesis H. (H: Cooperation flexibility, innovation flexibility, innovation performance and business performance are higher among smart service manufacturing providers than non-smart smart service manufacturing providers). The processing of hypothesis H is described below. First, it was necessary to verify the normality by the Shapiro–Wilk test, as shown in the following Table 1.

Tab. 1. Results of the Test of Normality

Do you provide smart services, such as remote monitoring, remote diagnostics, remote repair, and so on?		Shapiro–Wilk test		
		Statistic	df	Sig.
External cooperation flexibility with customers	Yes	.790	51	.000
	No	.868	61	.000
External cooperation flexibility with suppliers	Yes	.946	51	.021
	No	.952	61	.017
Internal cooperation flexibility	Yes	.842	51	.000
	No	.930	61	.002
Innovation flexibility related to the product	Yes	.923	51	.003
	No	.942	61	.006
Innovation flexibility related to accompanying services	Yes	.916	51	.001
	No	.968	61	**.117**
Innovation performance	Yes	.964	51	**.129**
	No	.969	61	**.122**
Business performance	Yes	.918	51	.002
	No	.940	61	.005

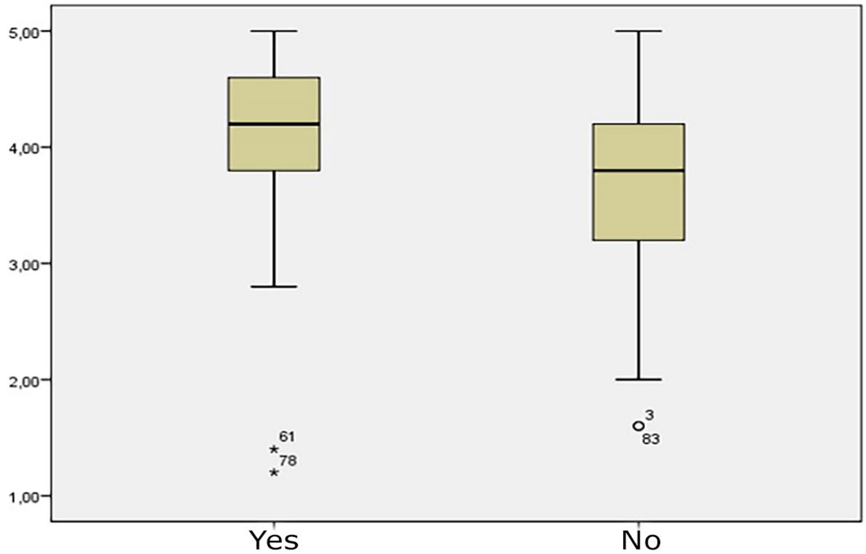

Fig. 1. Verification of extreme and remote observations

The normal distribution is fulfilled if the p-value of the normality test (Sig.) is greater than the selected significance level of 0.05. This is only true for selections marked in bold in Table 1 above. Parametric tests can only be used to compare selections that meet the normal distribution. To be sure, it can be seen whether violations of the normal distribution would cause any outliers or extremes, as shown in Fig. 1. To verify the occurrence of extremes and outliers, a box graph was used. It showed important extremes that distort parametric test results for the internal area only.

Furthermore, the extreme values in the area were removed, and the normality was tried again, see Table 2.

However, neither of these normal distribution selections were achieved (Internal cooperation flexibility NO — $p < 0.05$). The extreme values retained for the test in this file. For all areas except innovation performance, the non-parametric Mann–Whitney U test was used to verify the difference between enterprises that provide and do not provide smart services. For innovation performance, a parametric two-sample t-test could be used in both selections to meet normal data distribution (Table 3).

Based on the mean rank, smart service manufacturing providers achieved higher scores in the mentioned six areas (Table 3 and Fig. 2).

According to Fig. 2, the greatest differences in the mean rank of surveyed areas between smart service manufacturing providers and non-smart service manufacturing providers were in the area of internal cooperation flexibility, innovation flexibility related to the product, innovation flexibility related to accompanying services and business performance. The Mann–Whitney U test (Table 4) was used to ascertain whether this score is statistically significantly different from non-smart service manufacturing provider.

A statistically significant difference was found in the areas of internal cooperation flexibility, innovation flexibility related to the product, innovation flexibility related to accompanying services and business performance ($p < 0.05$). There was no statistically significant difference in the external cooperation flexibility with customers and external cooperation flexibility with suppliers n ($p > 0.05$). In addition, a two-sample t-test was carried out (Table 5), to determine whether smart service manufacturing providers differed in innovation performance from non-smart service manufacturing providers.

Tab. 2. Results of the Test of Normality after the removal of extreme values

Do you provide smart services, such as remote monitoring, remote diagnostics, remote repair, and so on?		Shapiro–Wilk test		
		Statistic	df.	Sig.
Internal cooperation flexibility	Yes	.956	49	.063
	No	.930	61	.002

Source: elaborated by the author based on obtained data.

Tab. 3. Average ranking of areas

Do you provide smart services, such as remote monitoring, remote diagnostics, remote repair, and so on?		N	Mean Rank
External cooperation flexibility with customers	Yes	51	62.05
	No	61	51.86
	Total	112	
External cooperation flexibility with suppliers	Yes	51	61.02
	No	61	52.72
	Total	112	
Internal cooperation flexibility	Yes	51	67.40
	No	61	47.39
	Total	112	
Innovation flexibility related to the product	Yes	51	67.91
	No	61	46.96
	Total	112	
Innovation flexibility related to accompanying services	Yes	51	68.24
	No	61	46.69
	Total	112	
Business performance	Yes	51	65.81
	No	61	48.71
	Total	112	

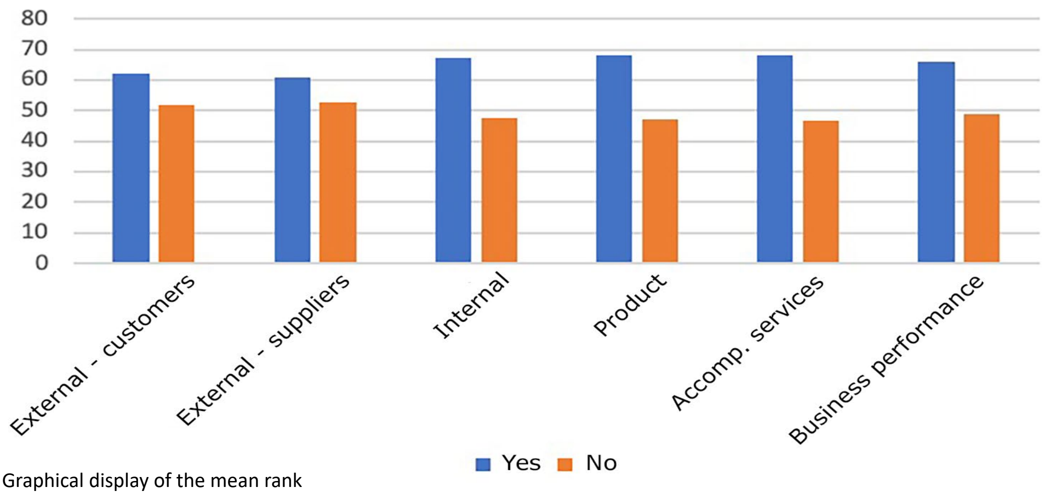

Fig. 2. Graphical display of the mean rank

Tab. 4. Mann–Whitney U test results (Grouping Variable: Do you provide smart services, such as remote monitoring, remote diagnostics, remote repair, and so on?)

	External cooperation flexibility with customers	External cooperation flexibility with suppliers	Internal cooperation flexibility	Innovation flexibility related to the product	Innovation flexibility related to accompanying services	Business performance
Mann–Whitney U Test	1272.500	1325.000	999.500	973.500	957.000	1080.500
Asymp. Sig. (2-tailed)	.095	.177	**.001**	**.001**	**.000**	**.005**

Tab. 5. Descriptive statistics of innovation performance according to smart service provision (Grouping Variable: Yes, No)

Do you provide smart services, such as remote monitoring, remote diagnostics, remote repair, and so on?		N	Mean	Std. Deviation
Innovation Performance	Yes	51	3.3490	.64105
	No	61	3.1705	.75880

Tab. 6. Results of two-sample t-test (Grouping Variable: Yes, No)

	Levene's Test for Equality of Variances		t-test for Equality of Means				
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Innovation Performance Equal variances assumed	.522	.472	1.330	110	**.186**	.17853	.13428

Based on the mean, smart service manufacturing providers achieved a higher innovation performance score. A two-sample t-test (Table 6) was used to determine whether this score was statistically significantly different from that of non-smart service manufacturing providers.

There was no statistically significant difference in innovation performance ($p > 0.05$).

In summary, a statistically significant difference among smart service manufacturing providers was demonstrated in the areas of internal cooperation flexibility, innovation flexibility related to the product, innovation flexibility related to accompanying services and business performance ($p < 0.05$). It can be said that if manufacturers provided smart services, they were better at internal collaboration flexibility, innovation flexibility related to the product, innovation flexibility related to accompanying services and business performance.

4. Discussion of the results

As mentioned above, current electrotechnical SMEs that provide smart services do not yet evaluate the potential financial benefits of including them in the offer. The potential has not yet been recognised for more advanced use-oriented or result-oriented services (Kozłowska, 2020a,b). The paper aimed to identify the importance of a smart service for cooperation and innovation flexibility and innovation and business performance, thus trying to contribute to a better understanding of the potential benefits of smart services for manufacturers.

Nowadays, there is no publicly available empirical study on the financial benefits of smart services for companies in the electrical engineering industry in the Czech Republic. Even if different companies implemented the same smart services, the benefits would be different for each company and measured using different parameters depending on the line of business, business model, management style and current life-cycle stage. The benefit of these services can, therefore, be measured and demonstrated only in a specific company, by monitoring the development of parameters that the company wants to improve by implementing a smart service.

The reasons for not monitoring the financial benefits may be the certainty of the inclusion of smart services in the range of services. Moreover, so far, the manufacturers tended to "tune" the smart services. A longer time horizon is clearly suitable for evaluation in each company. The benefit of these services can, therefore, be measured and demonstrated only in a specific company by monitoring the development of parameters that the company wants to improve by their implementing. Based on the results of quantitative research, there is a statistically significant difference in manufacturing companies providing smart services in the areas of internal cooperation flexibility, innovation flexibility related to the product, innovation flexibility related to accompanying services and business performance ($p < 0.05$).

Similar results related to business performance were shown in some research, where new technologies had a positive impact on business performance (Lopéz-Nicolás et al., 2010; Soto-Acosta et al., 2016). Also, Soto-Acosta et al. (2014) informed that SMEs aimed for new technologies that would allow for a better closeness with the external environment. Companies with greater confidence in services clearly achieved better revenue profitability and improved their value (Fang et al., 2008) and used best practice or training, which contributed to better business performance through the quality of service, productivity, profitability and innovation (Brewster et al., 2016). However, the efficient allocation of resources required the emphasis on the company's innovation strategy (Revilla et al., 2016). The results confirmed a significant difference in both parts of innovation flexibility (related to the product and accompanying services).

The results of this research agree with the outcomes by Bjerke & Johansson (2015) showing that cooperation within a company and the industry stimulates innovation at the company level. These findings demonstrate that the proximity associated with organisational structures and technological relatedness facilitates the sharing of knowledge and ideas. Interestingly, working with partners within the same corporate group has a much stronger positive relationship to the likelihood of innovation than working with companies in the same industry. Companies in the same sector are "neighbours" because they use similar technologies and operate in related markets, and, therefore, face similar technological challenges and similar business challenges (Bjerke & Johansson, 2015). Therefore, if companies belonged to the same sector, they could be assumed having a deeper understanding of the other party's problems and the processes associated with the creation and development of innovative ideas. This information can be related to the findings of this research, showing an impact of smart services on internal cooperation flexibility.

The knowledge shared between collaborating partners can be related, but it can also complement each other (Bjerke & Johansson, 2015). Companies are aware that territorial servitisation is a process linking services and industry and can increase the local impact of production activities on regional competitiveness and, thus, facilitate the dissemination of local knowledge (Lafuente et al., 2017). Servitisation of regions offers local production economies the opportunity to restore growth and maintain long-term competitiveness. However, local benefits of clustering do not always occur (Shearmur, 2012) as companies may prefer interactions with distant partners (Fitjar & Rodriguez-Pose, 2011) because relationships with close actors are not mandatory (Bathelt et al., 2004), and they can use other forms of proximity (Boschma, 2005) or cooperation can take place on several levels (Vissers & Dankbaar, 2016).

SMEs need to extend the source of flexibility across their borders. Similarly, Carlsson (1989) argued that flexibility is not necessarily limited to small businesses. Rather, it stems from the ability of small businesses to develop their capabilities using a variety of factors as sources of flexibility. SMEs are more likely to achieve flexibility through supply chain relationships and collaboration. As a result, for SMEs, flexibility should be promoted and increased by an appropriate supply-chain strategy (Liao et al., 2015).

Conclusions

Smart servitisation is clearly specific to SMEs, where due to frequently limited financial and personnel capacities, the implementation of smart technologies is more demanding. This paper aimed to find out if smart service manufacturing providers were different in cooperation and innovation flexibility and in innovation and business performance from non-smart service manufacturing providers. Smart servitisation requires collaboration across fixed boundaries because smart solutions work with third-party software products and service systems to implement smart autonomous ecosystems (Sklyar et al., 2019). Companies cannot operate separately from customers but must instead operate across fixed borders. Smart solutions must be designed to work and interact with solutions offered by many other manufacturers, used by customers, supplied by distributors, maintained by various service partners, and operated by third parties. Therefore, the integration of smart solutions across fixed boundaries is essential. This rapid transformation requires technological innovation, as well as business models and collaborative innovation, as manufacturers seek to configure their business models and practices to enable smooth collaboration (Kohtamäki et al., 2019).

Although the findings mentioned in this paper cannot be generalised, there are some influences on theory and practice for manufacturing companies. The scientific point of view of this paper contributes in two specific ways: first, in the presentation of the interconnection of smart services and cooperation flexibility, innovation flexibility, innovation performance and business performance; and second, in the identification of the impact of smart services in manufacturing SMEs and in finding out which areas affect the provision of smart services. A statistically significant difference in smart service manufacturing providers was demonstrated in the areas of internal cooperation flexibility, innovation flexibility related to the product, innovation flexibility related to accompanying services and business performance ($p < 0.05$). Combining servitisation and digitalisation can help a company to be less dependent on travel and human interaction (Rapaccini et al., 2020). However, the transformation needs the development and implementation of digital offerings, which are usually a long-term process (e.g., Tronvoll et al., 2020) that should have an intentional impact on the business model of the company (Paiola & Gebauer, 2020).

The practical point of view can be seen in the evaluation of the impact of smart services on manufacturing SMEs, namely, the impact of smart services on cooperation flexibility, innovation flexibility, innovation performance and business performance. Recently, Suppatvech et al. (2019) identified a series of benefits and factors of smart servitised business model. According to the paper, an advanced, service-oriented business model based on smart technologies needs close collaboration with different stakeholders and the development of innovative offerings that alight with customer needs (Paiola & Gebauer, 2020). However, Kohtamäki et al. (2019) noted that current company structures did not seem to be adequately adapted to the use and offering of smart services. Furthermore, Paiola & Gebauer (2020) noticed that only a few "prepared" companies could be evaluated as having the "full" leverage of smart technologies for smart servitisation. The findings can have a positive influence in several areas; therefore, they can be important factors for many manufacturing companies which still need some persuasion to offer smart services. The integration of digital technologies into service innovation is leading to the development of smart services and a new business model (Jaspert & Dohms, 2020).

The limitations of this paper and research are related to the orientation on one specific segment of manufacturing, namely, electrotechnical companies, where only manufacturers of final electrotechnical products (systems) were chosen. These products (systems) can monitor their activities during their operation, keep the customer informed, and also transmit this information to the manufacturer, which exactly corresponded to the concept of smart services in this research. Also, for a higher degree of generalisation, it would be better to have a larger sample of manufacturers.

Future research will be based on the findings mentioned in this paper and is planned to focus on the issue of operational indicators monitoring the impact of smart services. It would be useful to find out which operational indicators are best to monitor by manufacturers and why, in what time period and based on the findings, try to prepare a possible comparison or methodology for evaluating the impact of smart services.

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Erratum

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Internet-based consumer co-creation experience of the new product development proces

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The last name of Dariusz Siemieniako was misspelled as Siemeniako. For the reader’s convenience, the corrected author line appears below:
Viktoria Khrystoforova, Dariusz Siemieniako

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