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Robotic Process Automation (RPA) adoption: a systematic literature review

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ABSTRACT
Robotic process automation (RPA) is a recent technology that has recently become increasingly adopted by companies as a solution for employees to focus on higher complexity and more valuable tasks while delegating routine, monotonous and rule-based tasks to their digital colleagues. The increased interest, reflected in the increasing number of articles regarding approaches and test cases, has triggered the necessity for a summary that could extract the more generalisable ideas and concepts about these software robots. This paper used a Systematic Literature Review (SLR) approach to find and synthesise information from articles obtained on this subject. This research identified the most general implementation approaches of successful RPA adoption cases, observed benefits, challenges commonly faced by organisations, characteristics that make processes more suitable for RPA, and research gaps in the current literature. The findings presented in this paper have two purposes. The first is to provide a way for companies and organisations to become more familiar with good practices regarding the adoption of robotic process automation. The second is to foster further research on the subject by complementing the current knowledge and proposing new paths for research.

KEY WORDS
RPA, robotic process automation, software robot, digital worker, adoption, implementation

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Introduction

Robotic process automation (RPA) is a recent technology that promises to generate great returns on investment for companies and organisations (Hallikainen et al., 2018). For most, this concept may resemble physical robots wandering around offices performing human tasks and, as a result, contributing to job losses. In reality, it is a software solution that enables the automation of rule-based business processes and tasks by using software bots (Kregel et al.,

Costa, S. A. S., Mamede, H. S., & Silva, M. M. (2022). Robotic Process Automation (RPA) adoption: a systematic literature review. *Engineering Management in Production and Services, 14*(2), 1-12. doi: 10.2478/emj-2022-0012

2021; Lacity et al., 2015; Kokina & Blanchette, 2019). These bots work by imitating an employee's actions within one or several systems. They mimic what humans would do when entering or manipulating data using a computer (Januszewski et al., 2021).

The deployment of this virtual workforce to automate and streamline structured, manual, high-volume, repetitive, and routine tasks results in human workers delegating their tedious routine tasks to a digital worker, thus allowing them to focus on more difficult tasks (Choi et al., 2021; Hartley & Sawaya, 2019).

RPA is software that performs routine process tasks based on simple rules. Its umbrella of capabilities includes entering data, making simple calculations, reading and extracting data from Enterprise Resource Planning (ERP) systems, completing forms, responding to emails (Hartley & Sawaya, 2019), opening attachments, logging into applications, moving files or folders, scraping data from a webpage, extracting information from pdf files or images, and others. For physical documents, once scanned, both optical character recognition (OCR) and natural language processing (NLP) can be utilised to extract information for further processing (Hegde et al., 2018).

The use of robotic process automation (RPA) in organisations has rapidly increased in recent years and is projected to grow in the foreseeable future by 20–30 % per year, or USD 3.97 billion in 2025. RPA growth has also been predicted to happen at a rate of 32.8 % from 2021 to 2028. Organisations are adopting RPA with the motivation to reduce costs and improve efficiency, productivity, and service quality (Choi et al., 2021; Denagama Vitharanage et al., 2020; Harmoko et al., 2021).

As a result of this software implementation, productivity is expected to increase by 86 %, quality by 90 %, while office costs should reduce by 59 %. Due to these numerous benefits, robotics has become one of the main priorities for many organisations, also in the banking sector. As a result, it is indicated as a priority by 30 % of banks worldwide and by 45 % in Poland (Harmoko et al., 2021; Wojciechowska-Filipek, 2019).

Given the stated potential of RPA, it is paramount to understand how to adopt it in companies and organisations more efficiently. Therefore, it becomes necessary to further study and comprehend where its implementation is advisable, what challenges may arise and what benefits to expect from its adoption (Kokina & Blanchette, 2019; Parker & Appel, 2021). This paper seeks to collect and synthesise all available information on these topics, provide successful approaches to adopting robotic process automation within organisations, foster further research by exposing current research gaps and propose new directions for research.

This article is structured as follows: the background is given in Section 1, presenting the need for this review and providing a summary of previous reviews; Section 2 explains the planning, specifies each review question and defines data sources and search strategies; Section 3 explains data extraction and synthesis and presents the inclusion and exclusion criteria; Section 4 reports the key findings with strengths and weaknesses of the evidence in the current literature; Section 5 discusses this review against previous ones, considering differences in quality and results; and finally, Section 6 presents practical implications of this literature review for the RPA industry and unanswered questions and opportunities for future research.

1. Literature review

Companies using IT (information technology) or ICT (information and communication technology) are becoming exponentially more interested in RPAs (Marciniak & Stanisławski, 2021; Simek & Sperka, 2019). Also, the number of papers on this subject has also grown substantially (Fig. 1).

However, as the interest is so recent, there is an inherent lack of awareness or basic knowledge about the implementation resulting from the lack of theoretical foundations that allow for objective reasoning and the development of methodologies and frameworks (Marciniak & Stanisławski, 2021; Syed et al., 2020). Moreover, given the current increase in automation necessity driven by the pandemic, scientific research seems to be lagging behind, with a reduced number of articles discussing the role of RPA on organisations (Siderska, 2021).

The search found two literature reviews (Siderska,2020; Syed et al., 2020). This section summarises their content to be compared with this systematic review's findings. Both reviews refer to Lacity and Willcocks' definition of RPA as a software robot that mimics human actions allowing the automation of rules-based processes involving routine tasks, structured data, and deterministic outcomes. Other researchers go a step further into distinguishing between RPA and AI, with the former being more

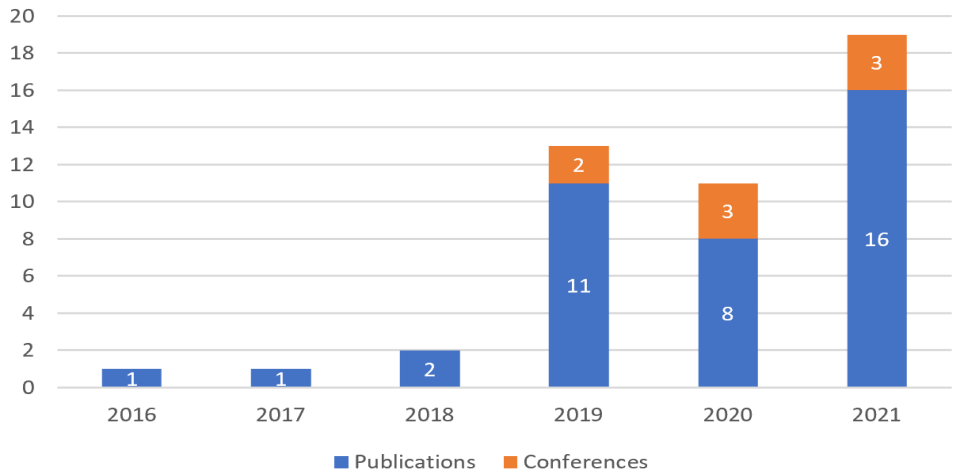

Fig. 1. Publishing year of articles selected for the literature review

rule-based and structured than the latter (Syed et al., 2020).

Other literature reviews studied methodologies for RPA adoption within organisations. As a result, these literature reviews provided company guidelines for approaching RPAs, approaches to initial task selection, reviews of frameworks for RPA roll-out, strategies for deployment and management of bots and plans for RPA's long-term success.

Other authors also presented literature summaries of the perceived potential capabilities of this technology. First, employee level capabilities are reviewed, presenting changes in their role and nature of their work. Next, organisation and process-related capabilities are discussed, including organisational changes. Also, several other types of capabilities are audited, such as process transparency, compliance, standardisation, organisation scalability, flexibility and control, and the ability to use process intelligence for decision making.

Both literature reviews evaluate the benefits of RPA adoption. While Siderska (2020) placed a greater emphasis on the positive impact of the technology by reshaping the work of the company's employees, Syed et al. (2020) focused more on the organisational repercussions of this adoption, for instance, higher efficiency, risk reduction, and compliance, quality of service, ease of implementation, and integration with company systems.

The two reviews also provide a bullet list containing all characteristics that cause some processes to be more suitable for automation than others. Both reviews state process complexity, frequency, and access to multiple systems as core factors for process fitness. Some authors go a step further and state other characteristics, such as data type and process maturity.

In other reviews, it is possible to find a summary of current leading RPA vendors and the technology positioning within the Open System Interconnection (OSI) model (Syed et al., 2020).

Finally, other researchers also discuss RPA integration with different technologies, such as artificial intelligence, natural language processing, process mining, big data, BPM/BPMS, and others.

2. Research Method

2.1. Research Questions

The aim of this systematic review goes beyond providing an overview of the current RPA landscape. It intends to answer how to efficiently implement this software, what benefits to expect from it, and what challenges may be needed to overcome. It also aspires to answer where RPA is most useful and what gaps in the literature still need to be filled. As a result, this research plans to answer the following questions:

- RQ1: Which are the approaches for successfully implementing RPA?
- RQ2: What are the benefits of implementing RPAs in organisations?
- RQ3: Which are the current challenges to RPA adoption?
- RQ4: Which process characteristics are more suitable for RPA implementation?

- RQ5: Which are the current RPA knowledge gaps in the literature?

2.2. Data sources and search strategy

A systematic literature review (SLR), or simply a systematic review, is a way to identify, evaluate and interpret all available research relevant to a particular research question, topic area, or phenomenon of interest. A literature review must be thorough and fair to be scientifically valuable. As it follows a predefined search strategy, a systematic review fairly synthesises existing work (Keele et al., 2007).

This SLR was conducted following Kitchenham's (2004) guidelines for systematic literature reviews. As a result, the process was divided into three stages: planning, reporting and conducting the review. During planning, the need for a review was identified, and the review protocol was clearly determined. In the case of this article, the literature was selected based on search criteria (Table 1).

A total of 486 studies were obtained as a result of this search.

3. Research results

The second phase of the SLR methodology focuses on selecting studies according to a given inclusion and exclusion criteria. Once the final studies are selected, data extraction, monitoring, and synthesis occur.

To obtain the final set of papers, a process with several filtering stages was executed over the first set of 486 collected papers (Fig. 2). After removing duplicates (184 papers), a total of 302 unique papers was obtained.

3.1. Inclusion and exclusion criteria

The titles and abstracts of these papers were read and led to their classification into three types: "accepted", "rejected", and "maybe". In total, 226 papers were excluded because they did not comply with the inclusion and exclusion criteria. Introductions of the remaining 76 papers, including types "maybe" and "accepted", were fully read and resulted in the further removal of 15 papers due to inaccessibility/an unknown language, five papers that casually mentioned RPA in a broad spectrum but did not fully explore the theme, and five papers that explored intelligent process automation (IPA).

A final set of 47 papers from different academic journals and conferences was obtained, including two literature reviews. The final collection had three articles published in the Journal of Information Technology Teaching Cases by SAGE. Other academic journals, such as Accounting Horizons by the Ameri-

Tab. 1. Search criteria

Element	Research Details
Source	EBSCO
Final Search String	AB ("Robotic Process Automation" or "Hyperautomation" or "Software Robotics" or "Software robot" or "Digital Worker" or "Business Process Automation" or "Process Automation") AND AB ("Implementation" or "Adoption")
Search Strategy	Articles in academic journals or conference materials without a date range limit
Results	486

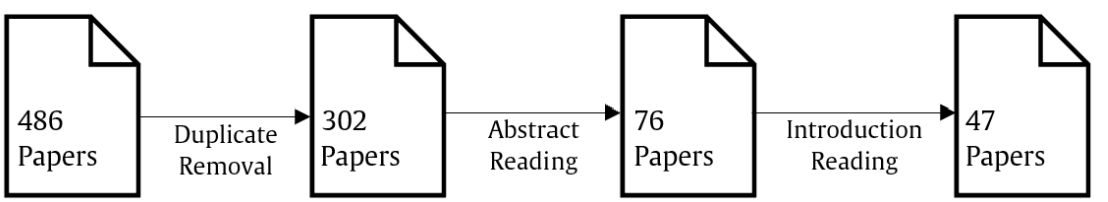

Fig. 2. Paper filtering process

can Accounting Association, International Journal of Accounting Information Systems by Elsevier, and MIS Quarterly Executive by Association for Information Systems and Sustainability by MDPI, contributed two articles each, while all the remaining articles were from distinct academic journals and conferences.

3.2. Key findings

3.2.1. RQ1: RPA implementation approaches

When analysing the selected set of articles, it was possible to identify that although RPA implementations differed from each other based on several factors, such as company size, maturity, and area of work, there were still some common denominators (Table 2).

Most companies followed a four-stage implementation framework consisting of identifying tasks, redefining processes from AS-IS to TO-BE, developing a bot, and, finally, monitoring its actions (Huang & Vasarhelyi, 2019). Other companies adopted a similar five-stage framework, including a testing phase after developing the bot and before its deployment (Gex & Minor, 2019).

Regarding regular approaches for adoption, most implementations started with a proof of concept (PoC), which intended to demonstrate RPA capabilities and potential for the company. Low-complexity, high volume/value processes were regularly chosen as PoC to achieve what some literature calls "quick wins" (Gex & Minor, 2019; Lacity et al., 2015; Flechsig et al., 2021).

A common solution in companies adopting RPA is a Centre of Excellence (CoE). When compared to outsourcing, a CoE provides critical benefits, such as familiarity with the processes, access to confidential information, and the environments where the robots will be implemented, facilitating bot testing and deployment (Vokoun & Zelenka, 2021; Huang & Vasarhelyi, 2019).

Research articles also highlighted the importance of RPA integration into the company's culture. Aiming to achieve this cultural shift, organisations hosted regular RPA Seminars, where RPA potentials and benefits were showcased through test cases, and appointed RPA Ambassadors, who would foster

Tab. 2. RPA implementation approaches

Approach	Sources
Proof of Concept	Huang & Vasarhelyi (2019); Raza et al. (2019); Gotthardt et al. (2020); Kokina & Blanchette (2019); Kossukhina et al. (2021); Hallikainen et al. (2018); Simek & Sperka (2019); Hegde et al. (2018); Carden et al. (2019); Lacity et al. (2015); Flechsig et al. (2021); Schuett (2019)
Center Of Excellence	Huang & Vasarhelyi (2019); Wojciechowska-Filipek (2019); Kokina & Blanchette (2019); Ågnes (2021); Kedziora & Penttinen (2021); Marciniak & Stanisławski (2021); Hegde et al. (2018); Flechsig et al. (2021); Schuett (2019)
Training	Wewerka et al. (2020); Wojciechowska-Filipek (2019); Kossukhina et al. (2021); Hallikainen et al. (2018); Viale & Zouari (2020); Fernandez & Aman (2018); Hegde et al. (2018); Willcocks et al. (2017); Flechsig et al. (2021)
RPA Ambassadors	Wewerka et al. (2020); Kedziora & Penttinen (2021); Hallikainen et al. (2018); Viale & Zouari (2020); Vokoun & Zelenka (2021); Gex & Minor (2019); Schuett (2019)
Removal of Fear of Job Loss	Wewerka et al. (2020); Ågnes (2021); Hallikainen et al. (2018); Simek & Sperka (2019); Lacity et al. (2015); Lemaire-Harvey & Harvey (2020); Siderska (2020)
RPA Seminars	Wewerka et al. (2020); Hallikainen et al. (2018); Parker & Appel (2021); Flechsig et al. (2021); Schuett (2019); Lemaire-Harvey & Harvey (2020)
Communication Expert-Developer	Huang & Vasarhelyi (2019); Wojciechowska-Filipek (2019); Ågnes (2021); Hallikainen et al. (2018); Hegde et al. (2018)
Data and Task Standardisation	Kokina et al. (2021); Kokina & Blanchette (2019); Fernandez & Aman (2018); Hegde et al. (2018)
Back-Up Strategies	Kokina et al. (2021); Kokina & Blanchette (2019); Hallikainen et al. (2018)

a positive outlook on the technology used at the company. It was also critical to remove the workers' fear of job loss, usually achieved by showing RPA benefits and reframing its implementation as a way to free employees from tedious tasks and allow them to work on higher complexity issues rather than as a means to replace them (Ågnes, 2021; Marciniak & Stanisławski, 2021).

Other recurrent characteristics of successful implementations include training employees to understand and work with RPA, focusing on good communication between process experts and RPA developers, standardising data and tasks, and having backup strategies in place if an RPA deployment fails.

3.2.2. RQ2: RPA benefits

Several benefits seem to arise from the successful adoption of these digital workers within an organisation. This section analyses the benefits found in the literature (Table 3).

The most mentioned benefit across the articles was RPA performing more tedious and monotonous work to allow workers to focus and invest their time in more complex, meaningful tasks that provide more value to the company (Kaya et al., 2019). Another observed benefit was that as a result of performing new or more meaningful tasks, employees would also invest more time in developing new skills to become more qualified at their specific job (Ågnes, 2021).

The handling of repetitive and tiring tasks by RPA also contributed to a lower error rate due to the eliminated human errors. Unlike humans, bots do not get tired and, therefore, are not susceptible to making the same mistakes as humans (Ketkar & Gawade, 2021). On the other hand, automated processes are vulnerable to systematic errors resulting from deficient RPA programming (Gotthardt et al., 2020).

The selected articles emphasise improved customer service and satisfaction. This benefit resulted from several factors, such as faster and smoother process execution, leading to rapid responses to customer requests and employees feeling less pressured to rush through interactions with clients (Parker & Appel, 2021).

An observable quantitative benefit of successful implementations was process efficiency, achieved through cost savings, with articles reporting between 25 % and 75 % (Wewerka et al., 2020; Wojciechowska-Filipek, 2019), and through process time reduction, with companies stating that some processes would take a 10th of the time of what they used to (Wojciechowska-Filipek, 2019). Not only did business processes become more efficient, but the articles also highlighted the ability of bots to work at any time. As a result, not only

Tab. 3. RPA benefits

Benefit	Sources
More Insightful Work	Kokina et al. (2021); Denagama Vitharanage et al. (2020); Kokina & Blanchette (2019); Ågnes (2021); Viale & Zouari (2020); Kaya et al. (2019); Marciniak & Stanisławski (2021); Gex & Minor (2019); Parker & Appel (2021); Fernandez & Aman (2018); Hegde et al. (2018); Willcocks et al. (2017); Arias et al. (2020)
Reduced Process Hours	Wewerka et al. (2020); Wojciechowska-Filipek (2019); Gotthardt et al. (2020); Kokina & Blanchette (2019); Simek & Sperka (2019); Parker & Appel (2021); Shwetha & Kirubanand (2021); Carden et al. (2019); Willcocks et al. (2017); Arias et al. (2020); Harmoko et al. (2021)
Lower Error Rate	Denagama Vitharanage et al. (2020); Wojciechowska-Filipek (2019); Gotthardt et al. (2020); Kokina & Blanchette (2019); Ketkar & Gawade (2021); Simek & Sperka (2019); Kaya et al. (2019); Vokoun & Zelenka (2021); Flechsig et al. (2021); Arias et al. (2020)
Cost Saving	Wewerka et al. (2020); Wojciechowska-Filipek (2019); Kokina & Blanchette (2019); Kaya et al. (2019); Marciniak & Stanisławski (2021); Gex & Minor (2019); Carden et al. (2019); Willcocks et al. (2017)
Customer Service and Satisfaction	Denagama Vitharanage et al. (2020); Viale & Zouari (2020); Parker & Appel (2021); Willcocks et al. (2017); Arias et al. (2020); Harmoko et al. (2021)
Working 24/7	Wewerka et al. (2020); Viale & Zouari (2020); Kaya et al. (2019); Marciniak & Stanisławski (2021); Flechsig et al. (2021)
Improvement in Staff Skills	Denagama Vitharanage et al. (2020); Ågnes (2021); Kaya et al. (2019); Parker & Appel (2021)
Standardisation	Wojciechowska-Filipek (2019); Marciniak & Stanisławski (2021)

do processes take less time, but the amount of time available to complete them also increases (Viale & Zouari, 2020). Most companies implementing RPA also felt the collateral benefits of standardising and improving their processes. It is necessary for documents to be structured and standardised and for processes to be stable and mature to integrate this technology. As a result, it is fair to classify standardisation as an advantage that emerges from the intent to adopt RPA (Wojciechowska-Filipek, 2019).

Other types of impact of these digital workers were the reduction in office space costs by 40 % (Wojciechowska-Filipek, 2019), more efficient coping with employee absence, as there was less redistribution of work because RPA could take over basic repetitive tasks, allowing for less office time and more remote work (Kossukhina et al., 2021), and business continuity during unexpected events, such as COVID-19 (Siderska, 2021).

3.2.3. RQ3: RPA challenges

The articles also reported on several challenges (Table 4), with some being more predominant than others and most originating from the newness of the technology.

As RPA is a recent technology, there is a lack of knowledge and experience in its implementation (Wewerka et al., 2020; Gotthardt et al., 2020). Not only do companies have issues with finding the right solutions for their situation, but there is also an internal resistance to adapting new culture. An example is the lack of employee awareness of the impact that this adoption may bring to their work (system, document structure and other changes) (Marciniak & Stanisławski, 2021).

The cultural resistance to change emerges on account of the lack of knowledge and experience with this software. Firstly, unless forced, some employees avoided implementing this new technology out of fear of losing their job, which led to less adherence (Fernandez & Aman, 2018). Secondly, some stakeholders failed to endorse and prioritise this adoption due to being comfortable with current work cultures (Viale & Zouari, 2020). Together, this lack of urge and desire to innovate poses a critical challenge to RPA implementation.

Although most companies have started to use digital documentation as a more flexible and modern way to store information, others are still lagging behind. The use of paper and unstructured documents is still a substantial impediment to RPA adoption in organisations (Wewerka et al., 2020). To automate any business process, companies must have structured documents stored digitally.

Understanding which processes are fit for automation is crucial for the success of the adoption of these digital workers. By contrast, attempting to automate unfit processes seemed to be a recurring challenge across organisations. Trying to automate manual, complex or highly fractional tasks (with multiple parties involved) is a challenge that companies face due to a lack of knowledge and preparation. In these cases, either redesigning the process or choosing a fitter process for automation appeared to be the best solution.

Tab. 4. RPA challenges

Challenge	Sources
Lack of Knowledge and Experience	Kokina et al. (2021); Saukkonen et al. (2019); Wewerka et al. (2020); Gotthardt et al. (2020); Kokina & Blanchette (2019); Marciniak & Stanisławski (2021); Hegde et al. (2018); Lacity et al. (2015); Flechsig et al. (2021)
Employee and Stakeholder Resistance	Saukkonen et al. (2019); Gotthardt et al. (2020); Viale & Zouari (2020); Marciniak & Stanisławski (2021); Fernandez & Aman (2018); Willcocks et al. (2017); Flechsig et al. (2021)
Access and Security Issues	Kokina et al. (2021); Raza et al. (2019); Gotthardt et al. (2020); Kokina & Blanchette (2019); Marciniak & Stanisławski (2021); Schuett (2019)
Data Incompatibility	Wewerka et al. (2020); Januszewski et al. (2021); Gotthardt et al. (2020); Hegde et al. (2018)
Lack of Documentation	Kokina & Blanchette (2019); Vokoun & Zelenka (2021); Schuett (2019)
Unfit Processes	Viale & Zouari (2020); Hegde et al. (2018); Siderska (2020)

Access and security are also among key issues for RPA implementations. Access to resources has always been managed by humans. However, with software robots, new measures must consider robots' access to information (Raza et al., 2019; Schuett, 2019). In the same way, current security practices do not consider the existence of digital workers, and successfully implementing a new security framework constitutes a significant challenge to organisations (Kokina et al., 2021). The novelty of the software and the resulting lack of documentation makes it challenging for companies to adopt RPA as there are currently no standards and methodologies in place (Vokoun & Zelenka, 2021).

3.2.4. RQ4: RPA suitability characteristics

In this section, the paper aims to answer what characteristics make a process suitable for automation according to the articles (Table 5).

The first suitability characteristic is for the process to be rule-based. Processes of this kind follow a concrete set of rules to achieve a given purpose. Decisions do not require judgment and can therefore be automated through if–then decision trees.

Another important feature for the automation of a process is maturity. The process should be subject to minimal changes in the near future. Outcomes and costs are easier to predict, and exceptions are less likely to arise. As a result, automation changes are also less likely, and benefits can be estimated by comparison with the process history.

Structured data and a standardised format for documents providing the information are crucial for processes to be suitable for automation. Structuring allows a software bot to find the required data expected for processing. Otherwise, it would be hard for the bot to fetch the data, and it would be prone to errors due to mistaking different information fields. Data should also be digital, through digitalisation if necessary, for the RPA to access and then process it. Although it is possible to read scanned documents using optical character recognition (OCR) this technology tends to have a more successful implementation with the digital format of data that eliminates the possibility of document misreading (Januszewski et al., 2021).

Routine processes that occur according to a given periodicity are more apt for automation. A given event that may be an action or a set moment in time (for example, every day at noon) can trigger the robot. As a result, without any human interference, the RPA may perform a given task automatically.

High volume processes are the ones performed frequently or by several people. Any organisation should consider such tasks a priority for automation as they yield the highest potential benefits and return on investment (ROI).

Tab. 5. RPA suitability characteristics

Characteristic	Sources
Rule-based	Kokina et al. (2021); Kokina & Blanchette (2019); Kedziora & Penttinen (2021); Hallikainen et al. (2018); Viale & Zouari (2020); Marciniak & Stanisławski (2021); Hegde et al. (2018)
Mature	Wewerka et al. (2020); Viale & Zouari (2020); Vokoun & Zelenka (2021); Hegde et al. (2018); Siderska (2021)
Structured Data	Kokina & Blanchette (2019); Simek & Sperka (2019); Vokoun & Zelenka (2021); Marciniak & Stanisławski (2021); Siderska (2021)
High Volume	Wewerka et al. (2020); Kokina & Blanchette (2019); Viale & Zouari (2020); Hegde et al. (2018); Siderska (2021)
Digital Data	Wewerka et al. (2020); Kokina & Blanchette (2019); Vokoun & Zelenka (2021); Siderska (2021)
Routine	Kokina et al. (2021); Wewerka et al. (2020); Choi et al. (2021); Marciniak & Stanisławski (2021)
Few Exceptions	Kokina et al. (2021); Viale & Zouari (2020)
Multiple Systems	Kokina & Blanchette (2019); Viale & Zouari (2020)

Process suitability for automation has several exceptions. Their automation often requires more time than their performance. Besides, the automation is more likely to fail and will need adjusting. Therefore, tasks with few exceptions are more suitable for automation as their RPA is easier to develop, monitor and maintain.

Another important characteristic of suitability is for the process to interact with multiple systems. As a result, the RPA implementation automates a part of the process and acts as a top layer providing integration between different systems.

3.2.5. RQ5: RPA research gaps

Like most technologies, RPA is in perpetual change, and consequently, new themes and questions arise, leaving research gaps to be investigated and filled. This section analyses potential areas for future research suggested in the literature that may help in further understanding of RPA (Table 6).

Regarding the impact of RPA on workers' skills, two common questions were frequently identified: capabilities needed to handle RPA and skills and knowledge obsolete due to this implementation (Kokina et al., 2021; Vokoun & Zelenka, 2021). As previously stated, most articles mention a shift in the worker's responsibility to more complex and creative tasks. However, they fail to provide a tangible description of what these new tasks embody.

Another opportunity for research lies in the RPA implementation. Being such a recent technology, RPA lacks concrete guidelines for implementation and follow-up procedures. Future research should seek to provide a framework for successfully implementing RPA in organisations in a way that follow-up procedures and monitoring are minimised (Wewerka et al., 2020; Siderska, 2021; Florek-Paszkowska et al., 2021).

Although RPA is among the most researched fields, its benefits still have room for investigation. Due to the growing body of research, companies are becoming more aware of factors that become critical for the success of this technology. As such, future research can try to understand how benefits from early adopters differ when compared to followers that are more aware of the technology's potential and downfalls (Wewerka et al., 2020; Vokoun & Zelenka, 2021).

The final identified research gap across the selected articles regards the future of RPA. There are significant research opportunities concerning what process, data, and integration-related functionalities are being developed and the future direction of RPA with AI incorporation (Kokina & Blanchette, 2019; Siderska, 2021).

4. Discussion

In this section, the paper compares the results of this systematic literature review with those of others. Relationships between the findings of this and other reviews are pinpointed, particularly considering the differences in the obtained results.

Given the recent increase in adoption and consequent stability of this new technology, the literature exposes new patterns emerging across all organisations. These patterns are observable when analysing the tables of key findings on each proposed research question. As a result of this literature review, it became clear that papers present converging opinions. A significant portion of the selected articles highlights similar adoption approaches, challenges, benefits, process characteristics, and research gaps.

With regard to implementation, as previously mentioned, organisational guidelines for adopting

Tab. 6. RPA research gaps

Research Gap	Sources
Further benefits research	Wewerka et al. (2020); Denagama Vitharanage et al. (2020); Kokina & Blanchette (2019); Januszewski et al. (2021); Vokoun & Zelenka (2021)
RPA impact on job characteristics	Kokina et al. (2021); Kokina & Blanchette (2019); Vokoun & Zelenka (2021); Siderska (2021)
Effective frameworks for RPA implementation	Vokoun & Zelenka (2021); Simek & Sperka (2019); Flechsig et al. (2021); Siderska (2021)
RPA evolution	Kokina & Blanchette (2019); Ketkar & Gawade (2021); Siderska (2021)

methodologies and frameworks, follow-up strategies, and plans for long-term success can also be found in other reviews. However, based on the most recent literature, this paper highlights the role of cultural changes in RPA implementation. As a result, this systematic literature review provides some additional implementation approaches to fostering the RPA adoption in the company's culture, such as removing the fear of job loss and promoting RPAs, whether through seminars or ambassadors.

Other reviews also evaluate the benefits of RPA adoption in the existing literature. As mentioned in the background, the former highlights the reshaping of work performed by company employees, while the latter places more emphasis on organisational benefits. Although approaching the same benefits, this SLR contributes by providing more recently discovered benefits resulting from the current COVID-19 pandemic panorama and, consequently, increased relevance of certain benefits. These benefits include the ability to work remotely, having more office space, and the capacity of companies to be functional despite employee absence.

As none of the selected reviews provided challenges for adopting RPA in an organisation, this SLR offered new information.

Characteristics that cause processes to be more suitable for automation are provided in both literature reviews. Although the results found in this and earlier reviews, this SLR goes a step further into laying out the reasoning for these characteristics to be suitable for automation.

Previous literature reviews date back to 2020 and 2019. Nineteen articles selected for this SLR were from 2021. As a result, the research gaps found in this and other literature reviews differed. With answers to previous research questions, the rapidly growing RPA exploration fosters new and more intriguing questions to be answered. Still, given how recent this technology is, the lack of a framework for companies to successfully employ RPA is a common denominator across the literature reviews for future research.

Conclusions

Recent implementations of RPA and consequent case studies provide a means to understand the potential impacts of software robots when successfully implemented and the mistakes that lead to their failure. RPA has provided organisations with clear resource benefits. RPA also upgraded the work of employees to more fulfilling tasks.

Although these digital workers provide many benefits, organisations still face various challenges due to a lack of frameworks and knowledge. This research sought to investigate the factors for successful implementations, benefits, challenges, and suitability of the technology. To conduct this research, a systematic literature review was adopted and a summary of the results. A table of sources for each concept was presented.

The analysis of 47 papers resulted in several main ideas:

- Overview of the adoption process of this technology across several companies mentioned in the test cases and several ideas for maximising the likeliness of its success.
- Analysis of RPA impacts and benefits in organisations where it was successfully implemented.
- Raising awareness of the biggest challenges to implementation for organisations to be ready to tackle them.
- A comprehensive summary of characteristics of suitable tasks and the reasoning behind them.
- Description of future avenues of research given the current RPA panorama and what remaining gaps in the literature.

The factors of successful adoption, challenges, benefits, and suitability characteristics of processes presented in this research can foster new research opportunities and provide organisations that struggle with innovation with a clearer understanding of the technology.

There seems to be a lack of guidelines for RPA implementation for smaller organisations. As they could reap the most rewards from task delegation to digital workers, this area could constitute crucial future research. Another opportunity for future work regards the applicability of the discussed frameworks by attempting to replicate them in an organisation.

Although process suitability for automation has been thoroughly researched, there is still room for future research to provide frameworks for process redesign with the goal of its automation.

Given that new frameworks and methodologies for RPA adoption continue being studied and improved, future work could potentially investigate new benefits that could arise from more efficient application and new challenges and threats to the current RPA landscape.

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A NOVEL DATA MINING APPROACH FOR DEFECT DETECTION IN THE PRINTED CIRCUIT BOARD MANUFACTURING PROCESS

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ABSTRACT

This research aims to propose an effective model for the detection of defective Printed Circuit Boards (PCBs) in the output stage of the Surface-Mount Technology (SMT) line. The emphasis is placed on increasing the classification accuracy, reducing the algorithm training time, and a further improvement of the final product quality. This approach combines a feature extraction technique, the Principal Component Analysis (PCA), and a classification algorithm, the Support Vector Machine (SVM), with previously applied Automated Optical Inspection (AOI). Different types of SVM algorithms (linear, kernels and weighted) were tuned to get the best accuracy of the resulting algorithm for separating good-quality and defective products. A novel automated defect detection approach for the PCB manufacturing process is proposed. The data from the real PCB manufacturing process were used for this experimental study. The resulting PCA-LWSVM model achieved 100 % accuracy in the PCB defect detection task. This article proposes a potentially unique model for accurate defect detection in the PCB industry. A combination of PCA and LWSVM methods with AOI technology is an original and effective solution. The proposed model can be used in various manufacturing companies as a postprocessing step for an SMT line with AOI, either for accurate defect detection or for preventing false calls.

KEY WORDS

quality management, defect detection, AOI, PCA, PCB, SVM

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Introduction

Quality inspection is a crucial stage in the assembling process of PCB manufacturing. It shows whether the board works correctly or not. Manual inspection of PCBs is laborious, time-consuming and imprecise as it is susceptible to human errors. Consequently, it is costly and ineffective. Currently, companies for PCB manufacturing use automated Surface-Mount Technology (SMT) lines to ensure better product quality and the manufacturing process continuity. The PCB

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manufacturing of the SMT assembly line goes through multiple steps of automatic handling. To ensure good quality and reduce the number of defects, advance inspection tasks, such as AOI, are becoming more popular. These quality inspection tasks are realised at different stages of the assembly process. The traditional defect detection methods have various disadvantages for application on big data sets, such as strong dependency on a designed template, time consumption, and high computational costs, which can be challenging for companies in the production environment (Hu & Wang, 2020). AOI placed on an SMT line inspects quality assurance of the processed PCB and, subsequently, can distinguish the chip assembly defects (Kim & Park, 2020). A digital camera and set of sensors are used in an AOI system for capturing the image and gathering data of each sample PCB product for further analysis. Due to the contactless measuring, the AOI tool is considered flexible, fast and effective compared to the usual electrical test equipment. Despite this, the AOI solution, in some cases, is not completely effective in defect detection and tends to report false positives. Some authors believe this to be caused by the natural limitation of AOI in the evaluation of visible defects only. Particularly, all observed visual differences are detected as defects, even though they can have no consequence on the actual functionality of a PCB (Soukup, 2010). Products evaluated by AOI as false-positive need to be manually recontroled using the human factor, which means additional costs. To make the detection of PCB defects more effective, a model should be proposed as an AOI postprocessing step to obtain better and more accurate results.

Therefore, the aim of this research is so to design a data mining model for effective recognition of defective and good-quality products. The AOI achieves an accuracy of 96.24 %. Therefore, the following research questions are posed: "Is it possible to use the SVM method and achieve a more effective solution for a quality recognition compared to AOI?", "Which SVM algorithm provides the best effectiveness?".

This paper is organised as follows. Section 1 introduces the current state of the solved problems and discusses various approaches used in PCB defect detection. Section 2 presents the used methodological approach, the source dataset, and evaluation metrics. Section 3 contains experimental results of the used individual algorithm settings. Section 4 compares the used models, discusses the key findings and defines the proposed model.

1. Literature review

Many authors have already examined the PCB quality control process, and most current papers focus on quality control using image processing. Most recently, Kumar, Shreekanth and Prajwal (2020) examined the effectiveness of different image processing algorithms in combination with the feature extraction method. Yin et al. (2019) proposed an improved local binary fitting level set method to improve the accuracy and efficiency of the PCB image segmentation. An automated defect detection approach for increasing the accuracy of the quality control process on PCB lines, which applies a SURF-based algorithm to AOI images, has been introduced by Hassanin et al. (2019). Chavan et al. (2016) proposed an innovative system based on image processing that combines various algorithms, such as Fault Detection Algorithm, Canny Edge Detection Algorithm and Contour Analysis. Wang, Zhao and Wen (2016) focused on detecting the PCB soldered dot using the image processing method. Kim and Park (2020) extracted two solder regions from a PCB image and then used a dual-stream CNN for defect classification. The proposed solution proves a higher performance and lower weight than can be obtained by conventional methods. The proposed method also improved the F1-score, reduced weight, and accelerated inference time compared to a single stream CNN. Hu and Wang (2020) introduced a deep learning PCB image detection approach, which builds a new network based on Faster RCNN. They also used the ResNet50 method together with Feature Pyramid Networks as the pillar for feature extraction, aiming for the effective detection of small defects on the PCB.

Zakaria et al. (2020) examined whether the machine learning approaches can significantly contribute to better PCB fault detection in the assembly line. They presented several different attitudes to PCB defect detection using various machine learning methods. This review showed that methods, such as random forests, neural networks, or probabilistic approaches, had been applied for PCB defect detection with the use of an AOI. But in the end, they concluded that the use of machine learning methods in PCB defect detection is rather minuscule. Reshadat and Kapteijns (2021) examined and compared different machine learning models applied to the output dataset from the AOI. They found that the K-Nearest Neighbors method achieved the best results for their case.

This research aims to propose an AOI process for better detection of low-quality PCBs. Defect detection is considered one of the essential requirements for quality control in PCB production. The independent AOI is inclined to often make false calls when the AOI evaluates the product as defective, but after a manual check, the product is reassessed as good quality. These false calls become expensive for the company when they are more frequent than correctly detected defective products. The AOI on the SMT line at the company that cooperated with this study realises almost 4 % of false calls, which is considered a high rate. The research authors aimed to find a solution or propose a model for the higher accuracy of defect detection. Based on the previous literature review (Bartova, Bina & Vachova, 2022), the chosen method for this classification task was the support vector machine (SVM). SVMs are currently a hot topic in the machine learning community, creating a similar enthusiasm now as previously encountered by Artificial Neural Networks. Far from being a panacea, SVMs yet represent a powerful technique with an intuitive model representation not only for outlier detection but for classification and regression in general (Meyer, 2020). In recent years, the SVM method has received considerable attention because of its superior performance in pattern recognition and regression (Cortes & Vapnik, 1995; Bores et al., 1995; Vapnik, 1995; Vapnik, 1997; Burges, 1998; Vapnik, 1999). The SVM method is useful for tasks such as defect detection and classification in manufacturing. Isa, Rajkumar, and Woo (2007) proposed a model which combines Discrete Wavelet Transform and Support Vector Machine for sensor data processing and further oil and gas pipeline defect classification. Ghosh et al. (2010) investigated the SVM performance of pattern classification of defects from images. They proposed an SVM-based multi-class model for defect pattern recognition and inspection of commonly occurring fabric defects. Most recently, Mahfuz et al. (2020) explored the SVM model for feature selection to increase accuracy and reduce the false-positive rate in defect detection.

Compared to other machine learning algorithms, SVM appears to be a suitable candidate for several reasons: high accuracy achieved in similar classification tasks, generalisation ability without source data limit preconditions, fast learning and evaluation, and, last but not least, its flexibility (Zhang et al., 2005, Zhang & Zhang, 2001). To improve the accuracy of the SVM method, some methods for data preprocessing can be used. To deal with the data complexity and diversity, Sun et al. (2013) used PCA and particle swarm optimisation (PSO) together with SVM within the analogue circuit fault diagnosis task. They applied PCA and data normalisation as preprocessing steps, then SVM for diagnosis itself, and PSO was finally used to optimise the penalty and the kernel parameters of SVM.

2. Research methods

The dataset used for this empirical study comes from the AOI system developed by Saki Corporation, whose four digital multifrequency projectors provide accurate 3D measurements for high-quality images. Based on these images, AOI evaluates the quality of the product and categorises it as either good-quality or defective. The defective products are then manually checked by a manufacturer and categorised as either defective or falsely categorised as such. The source dataset has 63093 products in total (0.22 % defects, 3.76 % false calls and 96.02 % quality products). Since the number of false calls is rather high in comparison with defective products, this study focused on the improvement of the quality evaluation process.

Based on a previously developed PRISMA-based systematic review (Bartova, Bina & Vachova, 2022), the method Support Vector Machine (SVM) was chosen for further research on effective defect detection. The PCA method for feature extraction was used as a preprocessing step. Based on Mujica et al. (2008), the methods for the dimensionality reduction of a data set are especially beneficial for working with high volume data.

This research is based on a combination of these two methods into one algorithm sequence. The research authors aimed to find the most effective type of the SVM algorithm and rate the effectiveness and accuracy of the proposed models.

2.1. Data set description

This study used a data file from the AOI line from an unnamed company, where the fitting of PCBs is automated on the SMT line. At the end of the assembling process, a control process was performed using the AOI technology. The data set had 63 396 products and 217 variables. The distribution of the products can be found in Table 1. For the model, the "false calls" products were reclassified as "pass" since they were good quality but misclassified by the AOI.

Tab. 1. Source dataset distribution

	PASS	FAIL	FALSE CALL
Products count	60582	165	2649
Percentage	2.56 %	2.26 %	2.18 %

2.2. Data preprocessing

Classification problems in quality assurance were characterised, for example, by many contributing features, considering the training set size or the imbalanced distribution of the dependent variable (Rokach & Maimon, 2006). The authors of this study faced analogical problems in their source dataset. For this reason, it was necessary to preprocess the data for better handling in the experimental phase of the research. The first step was to delete variables for which most of the data were missing. It was found that 148 variables did not contain values for more than 60 000 products; therefore, they were removed from the data file. Once constant and unimportant variables were removed from the remaining group of 68, only 25 variables were left. Then, the missing values were imputed by the predictive mean matching method. However, the dimensionality in the data set was still relatively high; consequently, the PCA analysis was used for feature extraction.

2.3. Model's evaluation

The most critical factor was the accuracy of the model since the research aimed to correct the classification of as many products as possible. The accuracy of different types of used SVM models was tested using the confusion matrix (Table 2).

Tab. 2. Confusion matrix

Confusion matrix		Actual class	
		Positive	Negative
Prediction	Positive	TP (true positive)	FP (false positive)
	Negative	FN (false negative)	TN (true negative)

The accuracy measure commonly employed for classifier performance evaluation is defined by Eq. (1).

$$Accuracy = \frac{TP + TN}{TP + FP + TN + FN} \quad (1)$$

Nevertheless, with many present negative occurrences (in this case, good-quality products), it is useful to measure the performance by ignoring the correctly predicted negative items. In this case, well-known performance measures, such as precision (P), recall (R), or other factors, can be used (Rokach & Maimon, 2006). Several measures were used for the evaluation of models within this research.

Tab. 3. Accuracy measurements

Measure	Derivations	Index description
Recall	TPR=TP/(TP+FN)	How many items of the "not passed QA" class are correctly recognised
Precision	PPV=TP/(TP+FP)	How many items classified as "not passed QA" are true "not passed QA"
Specificity	SPC=TN/(FP+TN)	Expresses the proportion of products whose test is negative (quality products) among all those that actually have no defect
Negative Predictive Value	NPV=TN/(TN+FN)	The probability that following a negative test result, an individual product will truly have no defect
False Positive Rate	FPR=FP/(FP+TN)	The probability that a false call will occur and a positive result will be given when the true value is negative
False Discovery Rate	FDR=FP/(FP+TP)	The expected rate of Type I errors: the result is a false-positive
False Negative Rate	FNR=FN/(FN+TN)	The probability that a true-positive item will be missed by the test

The calculation formulas of these factors are presented in Table 3. The currently used AOI solution shows too many false calls, so the False Discovery Rate is high (4.18 %). This research aimed to create a model decreasing the value of this factor.

It also evaluated two more factors: the number of vectors needed for accurate model creation and the time for model counting. According to Tseng et al. (2015), a lower number of support vectors needed signifies the robustness of the classifier. This study assumed that the lower number of vectors was better. This also correlated with the duration of the algorithm execution.

2.4. Feature extraction phase

In machine learning tasks, each additional feature in the dataset exponentially increases the requirement of data points to train the model. The learning algorithm needs an enormous amount of data to search for the right model in the higher dimensional space. Therefore, this study used the PCA analysis for the reduction of variables in the data. This caused the data transformation into fewer dimensions and acted as the summaries of the features.

PCA reduces data by their geometrical projection into lower dimensions, and there arise the so-called principal components (PCs). The goal is to find the best summary of the data using a minimum number of uncorrelated PCs. The first PC minimises the total distance between the data and their projection onto the PC, in other words, the first PC explains the largest variability portion of the original data (Kakkar & Narag, 2007).

The eigenvalue variance was used to extract the number of PCs for this study. The analysis also provided the proportion of total variance in all variables accounted for each factor. It is evident from the data that the eigenvalues descended rapidly from the first value. The first component accounted for approximately 19 % of the variance of the original 25 factors, but subsequent components accounted for much less.

Thus, using the eigenvalue selection for this study, it can be assumed that only five factors were retained as PCs across all categories and questions. These PCs cumulatively accounted for approx. 65 % of the total variance. This is visible on the scree plot (Fig. 1).

It can be observed that the first five principal components can represent more than 60 % of the information stored in 25 used variables. The increment of the next variables is exceptionally low compared to them, so for further research, this study used only five variables (PC1-PC5).

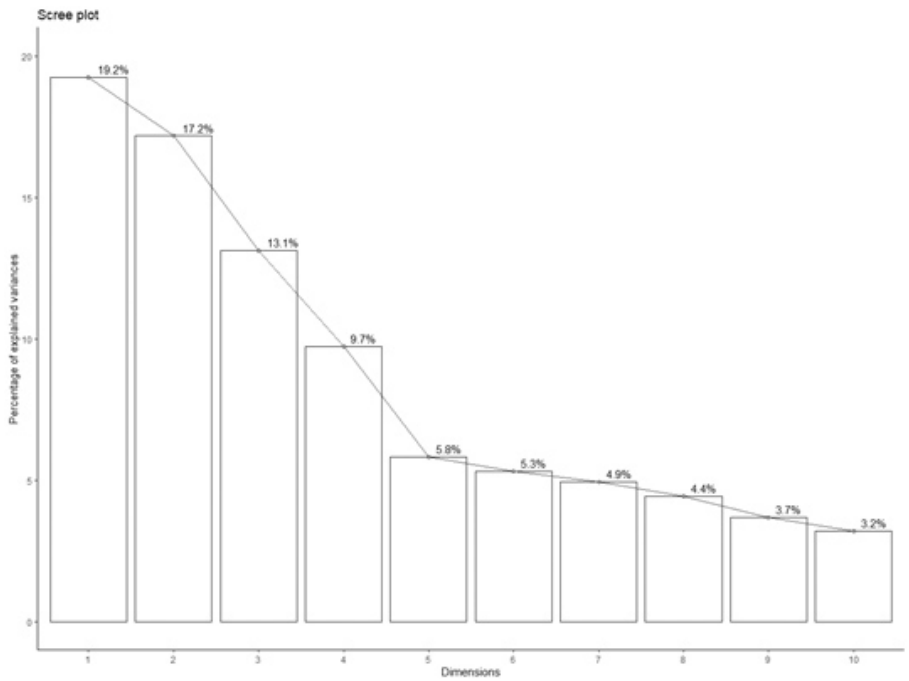

Fig. 1. PCA contribution — the scree plot

2.5. Support Vector Machine

Since SVM details are fully described in articles (Vapnik, 1998; Cristianini & Shawe-Taylor, 2000), this article offers a brief introduction to their fundamental principle. An SVM looks for the optimal hyperplane separating the two classes. The algorithm finds the optimal hyperplane by maximising the margin between the closest points of the two classes. For better work, mainly with non-linear data, kernel functions can be used. This research addresses the binary optimisation problem using a linear model, various kernels and weighted SVM models. Choosing different kernel functions produces various SVMs and may result in different performances (Burges, 1998; Aronszajn, 1950; Shawe-Taylor et al., 1998). Some work has already been done on limiting kernels using prior knowledge, but the best choice of a kernel for a given problem is still an open research issue (Williamson, Smola & Schölkopf, 1999; Chapelle & Schölkopf, 2002).

For SVM analysis, the data set was randomly divided into a training set (75 %) and a testing set (25 %). First, the model was tuned using the training data set; then, the created model was applied to the testing data set, and finally, the accuracy of the proposed model was evaluated. Different SVM algorithms were used for the prediction of defective products to achieve the best-fitted model.

3. Research results

At this stage of experiments, the research authors investigated the SVM models and their parameters for the successful detection of the defective products with the highest accuracy possible to find the most suitable model. Except for the linear SVM and different types of kernels, they also examined the weighted models.

For the use of the linear model and various kernels, different parameters were tuned, such as cost, gamma, and degree. The linear model had only one regularisation parameter C (cost). Parameter C controls the collation between variable misclassifications penalty and the margin width. A small value of the parameter C makes the constraints easy to ignore. This leads to a large margin. On the other hand, a large C value complicates the constraints disregard, which leads to a small margin. This parameter is also valid for all other models. For the purpose of finding the best model, the research authors tuned parameter C interval <0.01;100>. Unfortunately, the changing of the cost parameter did not influence the result accuracy at all.

When the data are not linearly separable, the various kernel functions can be used. The kernel functions are one of the important tricks of SVM. A kernel is a method of placing a two-dimensional plane so that it is curved in the higher-dimensional space (Boser, Guyon & Vapnik, 1992). There are several possibilities for the choice of this kernel function, including polynomial, sigmoid or radial basis (RBF). Additional parameter-slope gamma can be set for kernel models. Gamma is a hyperparameter that decides how much curvature we want in a decision boundary. When the parameter gamma is increased, then the decision boundary gets more curvature. First, the polynomial kernel was tried, which is a non-stationary kernel.

A kernel function represents the vectors' similarity in a feature space over polynomials of the original variables, allowing learning of non-linear models. In the case of the polynomial kernel, the value of cost and also the degree parameter of the SVC class need to be filled. However, the accuracy of the polynomial model does not reflect the changes in the used parameters. The best-achieved accuracy by the kernel polynomial function is 0.9979712 (99.8 %), which is the same as from the linear model. The next model, RBF (Gaussian) kernel, comes from a family of kernels where a distance measure is smoothed by an exponential function (Suo et al., 2008). RBF is the most used type of kernel function, mainly because it has a localised and finite response along the entire x-axis. Also, all the quality products have been correctly detected in this model, but all the defective products were wrongly assumed as good quality.

The last kernel function in this study was sigmoidal. As can be seen from the results in Table 4, the sigmoidal model results reflect the parameter changes the most, but on the other hand, the best accuracy is not higher than in the previous cases. Also, in the case of sigmoid SVM, the best-achieved result was 99.8 %, but no defective product was detected correctly.

All tuned models achieved the same result. All of the 15 735 quality products were correctly classified as good. However, the case was not as good with defective products. Out of 38 defects, all were misclassified as good-quality products (Table 5). The accuracy of the linear SVM was 0.9979712 (99.8 %). The model was not sufficient for fulfilling the set goal, even though the accuracy was high because no defec-

Tab. 4. Unweighted models accuracy

#	Cost	Lin.	Gamma	Rad. basis	Sig.	Dg.	Polyn.
1	0.001	0.998	0.0001	0.998	0.998	1	0.998
2	0.01	0.998	0.001	0.998	0.998	2	0.998
3	0.1	0.998	0.01	0.998	0.997	3	0.998
4	1	0.998	0.1	0.998	0.997	4	0.998
5	10	0.998	1	0.998	0.996	5	0.998
6	100	0.998	10	0.998	0.996	6	0.998

Tab. 5. Confusion matrix — unweighted models

Confusion matrix		Actual class	
		Positive	Negative
Prediction	Positive	0	0
	Negative	38	15735

tive product was correctly detected. For this reason, the data was assumed as not linearly separable.

Several models of different kernel functions were made, but none of them had sufficient accuracy. For this reason, the study continued searching for a model with satisfactory accuracy, especially a model able to detect defects even at the expense of a false-positive test of a small number of good-quality products. Based on some authors, weighted SVM (WSVM) could perform well in these classification tasks (Banjoko et al., 2019; Xanthopoulos & Razzaghi, 2014; Yang et al., 2007); therefore, it was used in this study as well.

3.1. Weighted SVM

The basic idea of the Weighted Support Vector Machine (WSVM) is assigning a different weight to each data point according to its relative importance in the class. Then, different data points have different contributions to the learning of the decision surface (Yang et al., 2007). Using a weighted linear SVM is better on such a data set than the simple linear SVM. Two separated regularisation parameters C1 and C2 are used instead of one. The weight of the penalty for misclassifying a good-quality product sample is represented by both parameters C1 and C2. The formula of the weighted support vector machine is expressed by Eq. (2).

$$Minimize_{w,b}\left(\frac{\| w \|^2}{2} + C_1 \sum_{i=1}^{n_1} \xi_i + C_2 \sum_{j=1}^{n_2} \xi_j\right) \quad (2)$$

where n_1 (respective n_2) is the number of quality products (respectively, defect products) in the training data. The parameters are then counted as can be seen in Eq. (3) and Eq. (4).

$$C_1 = \frac{1}{n_1} \quad (3)$$

and

$$C_2 = \frac{1}{n_2} \quad (4)$$

Of course, there are several approaches to setting the optimal weights.

The weights are only required for the algorithm training and are no longer used when the trained model is employed to predict the class label in the encoding process.

3.2. Weighted linear model

In the case of this study, when only several products with some defects are available in the dataset, a much higher weight must be attributed to them. Otherwise, the same result would probably be received as in previously run basic models, so that all good-quality products are correctly detected, but all defective products are misclassified. The attempt was made to heuristically try the SVM using different weights and different core functions. Then, the accuracy of the designed models was evaluated. First, the model was trained with a linear function. Table 6 provides the results of six runs of the SVM with

mentioned weights of classes. The model was created with 100 % accuracy using a 0.0004 weight for good-quality products and a 0.1618 weight for defective products. This model generated 3771 support vectors, which is rather many, but despite this, the training time was less than ten seconds, which is exceptionally good.

Tab. 6. Linear weighted model accuracy

#	W(PASS)	W(FAIL)	Accuracy	# of vectors	Time (s)
1	0.0000159	0.007353	0.9284551	15437	30:59
2	0.0000794	0.036765	0.9409149	8330	16:94
3	0.0001588	0.073530	0.9657025	6284	14:76
4	0.0003177	0.147059	0.9978426	4601	11:12
5	0.0003336	0.154412	0.9999560	4504	10:85
6	0.0003495	0.161765	1.0000000	3771	9:84

The following table provides a confusion matrix of the resulting compiled model (Table 7). It demonstrates that no product was misclassified using this model.

Tab. 7. Confusion matrix — the linear weighted model

Confusion matrix		Actual class	
		Positive	Negative
Prediction	Positive	38	0
	Negative	0	15735

Even though an optimal model was already found, weights were tuned for models with other functions to investigate whether it was possible to achieve a 100 % correct classification of the product quality with other models.

3.3. Weighted polynomial model

Different weights were tried with various parameter degree settings for a model using a polynomial function. The best-created model generated only 108 support vectors, and also, the training time was very short. However, as Table 8 demonstrates, the accuracy of this model was not sufficient compared to the previously mentioned model.

Tab. 8. Polynomial weighted model accuracy

#	Dg.	W(PASS)	W(FAIL)	Accuracy	# of vectors	T(s)
1	3	0.000350	0.161765	0.99943	1354	4:49
2	5	0.000350	0.161765	0.99982	260	1:83
3	6	0.000350	0.161765	0.99991	99	0:92
4	7	0.000350	0.161765	0.99978	61	1:15
5	6	0.000318	0.147059	0.99994	108	0:96
6	6	0.000477	0.220588	0.99981	73	1:08
7	4	0.000477	0.220588	0.99987	491	2:12

Table 9 summarises the confusion matrix of the best performed weighted polynomial model. Only one product was misclassified using this model and was incorrectly marked as defective even though it was of good quality. This is the Type I error.

Tab. 9. Confusion matrix — the polynomial weighted model

Confusion matrix		Actual class	
		Positive	Negative
Prediction	Positive	37	0
	Negative	0	15735

3.4. Weighted Radial Basis Model

Results of the WSVM model with a radial basis function are summarised in Table 10. This model also proved to have better accuracy compared to the unweighted models. However, in this case, the tuned class weights and the cost parameter achieved accuracy that was still slightly worse compared to both previously performed weighted models. It should also be underlined that the radial basis model shows some cost values, not only very high calculation time but also a high number of vectors. Generally, the lower value of the cost parameter causes the higher execution time and number of support vectors, and in contrast, the higher cost value shows better performance in both mentioned factors and also higher accuracy.

Tab. 10. Radial basis weighted model accuracy

#	W(PASS)	W(FAIL)	C	Acc.	# of vec.	T(s)
1	0.000159	0.073530	0.01	0.99759	43609	406:13
2	0.000159	0.073530	0.1	0.98593	43609	421:92
3	0.003971	1.838235	10	0.99943	753	6:26
4	0.000477	0.220588	0.1	0.98593	42926	424:05
5	0.000874	0.404412	10	0.99537	2093	17:14
6	0.015884	7.352941	0.1	0.99937	5120	40:07
7	0.015884	7.352941	100	0.99981	173	1:82

Tab. 11. Confusion matrix — radial basis weighted model

Confusion matrix		Actual class	
		Positive	Negative
Prediction	Positive	35	0
	Negative	3	15735

In Table 11, we can see the confusion matrix of the best weighted radial basis model, which achieved a 0.9998098 accuracy. Three products were wrongly detected as defective, even though they were of good quality. Even in this case, it is a first-order error.

3.5. Weighted sigmoid model

The last tuned model uses the sigmoid function. Several support vectors were generated for each algorithm run. The classification accuracy in both the training and testing data sets was noted. According to Table 12, the model's accuracy was significantly worse than in previous models. The best-achieved model showed an accuracy of only 74.89 %. The calculation time was rather high compared to the polynomial and linear weighted models, and the same could be said for the number of support vectors. Also, the cost parameter did not influence the evaluation factors markedly as it was with the radial basis model.

The worst results were achieved by the weighted sigmoid model, where 3951 products were incorrectly marked as poor quality (Order II error). On the other hand, nine products were wrongly classified as good quality (Table 13).

Tab. 12. Sigmoid weighted model accuracy

#	W(PASS)	W(FAIL)	C	Acc.	# of vec.	T(s)
1	0.003971	1.838235	10	0.748177	11362	138:65
2	0.000080	0.036765	100	0.746846	11590	132:33
3	0.008816	4.080882	100	0.748938	11334	143:06
4	0.015884	7.352941	1	0.747036	11315	134:62
5	0.013501	6.250000	0.1	0.733215	12696	143:03
6	0.162810	75.36765	0.01	0.736385	12475	139:75

Tab. 13. Confusion matrix — sigmoid weighted model

Confusion matrix		Actual class	
		Positive	Negative
Prediction	Positive	35	0
	Negative	3	15735

4. Discussion of the results

After the analysis of the obtained models and testing of the accuracy levels achieved by using different kernels, the following conclusions were drawn. Fifty models were created and checked according to parameters of accuracy, number of vectors and execution time. To compare the models, the accuracy was tested using the confusion matrix and several metrics, visualised in Fig. 2.

Type I error was shown by basic unweighted models that used not only the linear function but also all kernels. Although the accuracy of these models was rather high (99.8 %), all of them misclassified all the defective products and assigned them wrongly to the good-quality class. Since the correct detection of defective products was the main goal, the study continued by including the class weights in the model. The weighted models performed significantly better, and their comparison according to the different indexes can be seen in Fig. 2. Amongst all the models, the weighted linear kernel achieved a perfect 100 % of recall rate, while other kernels always misclassified some of the defective products. All three models (weighted linear, weighted polynomial and weighted radial) achieved 100 % precision, and interestingly, the weighted sigmoid model showed extremely poor

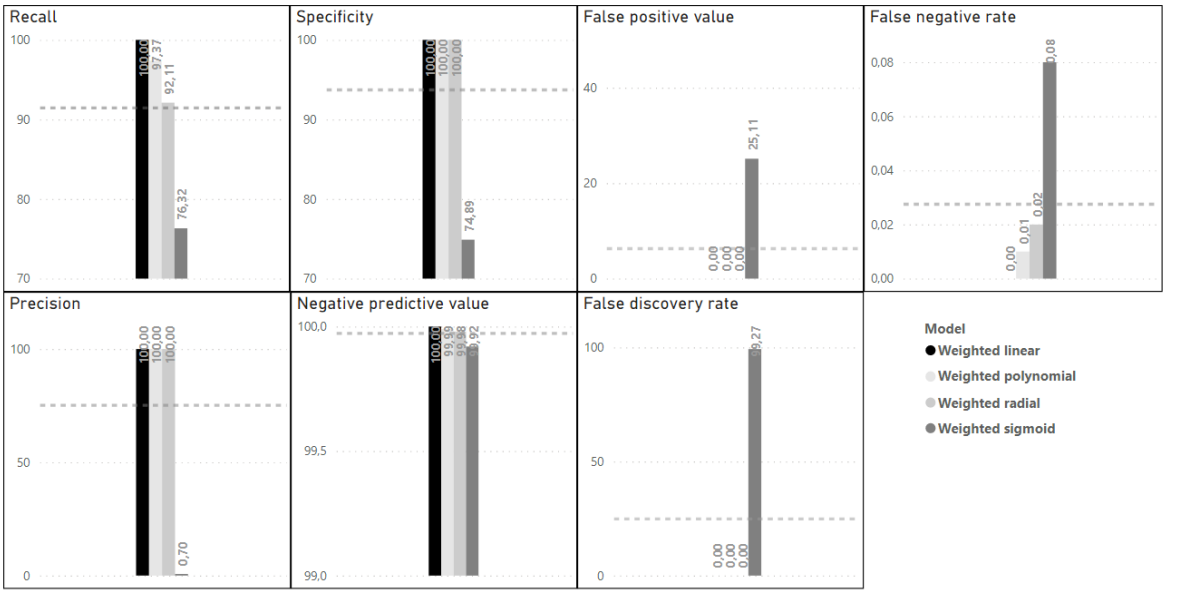

Fig. 2. Comparison of the weighted models' accuracy

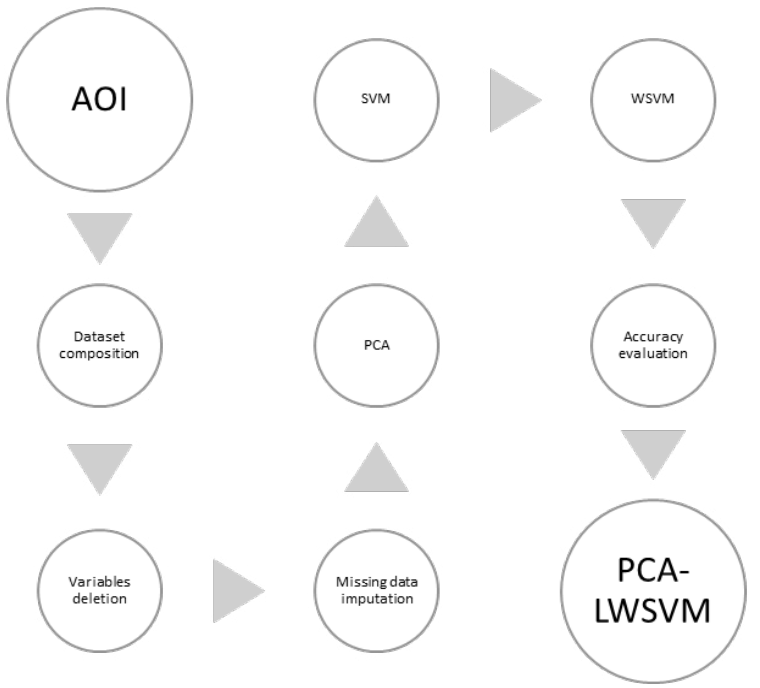

Fig. 3. Proposed model process

performance in this factor (<1 %). Differently from other used models, it had a remarkably high "false discovery rate", so this model mainly classified the products false positively (the weighted sigmoid model inclined to Type I error). In contrast, the weighted sigmoid model performed well compared to other models in the case of "negative predictive value". Based on the execution time performance and the number of supporting vectors, the best model was the polynomial weighted model. Unfortunately, this model showed worse accuracy than the linear weighted model. Consequently, the linear weighted model was evaluated as the best because the accuracy factor was definitely the most important for the study.

Fig. 3 demonstrates the used process leading to the resulting model. As was previously mentioned,

the AOI on the SMT line for PCB mounting was used as the starting point from which the source data was gathered. The next step was the deletion of the unnecessary variables and missing data imputation for data preprocessing

Then, the PCA method was used for dimensionality reduction, and five final variables were created for further analysis. Based on the previous literature review, the SVM supervised algorithm was chosen for defect detection. Once it was found that the basic linear SVM and different kernels did not provide a satisfactory accuracy of classification, the addition of class weights was attempted. Weighted models performed much better. The Linear Weighted Support Vector Machine (LWSVM) model achieved 100 % accuracy. Therefore, the result of this study is the PCA-LWSVM model suitable for defect PCB detection implemented after image processing via AOI.

Conclusions

The paper presented different SVM algorithms that can be utilised for defective PCB detection on the output of the SMT line with AOI. This study aimed to investigate the optimal supervised parameters and feature representations. In the studied case, the weighted SVM model performed better than the linear SVM and different kernels. The resulting model combines the PCA feature extraction method and the WSVM classification algorithm. Different weights were tuned to find that 0.0003494449 for good quality products and 0.1617647059 for defective products proved to perform the best. AOI, which was originally used for defect detection, misclassified 4.18 % of samples and mismarked them as defective, while the proposed PCA-LWSVM model successfully classified both good-quality and defective products with a 100 % accuracy.

The main limit of the study can be the assumption that other models with a 100 % accuracy can be tuned and achieve even better performance from other points of view (the calculation time, weightless model, etc.). The weighted polynomial model performed very well and could be the subject of further investigation. Moreover, if certain data sets were used, the proposed model could be insensitive, and this means that different data sets may lead to various "suboptimal" models. It should also be mentioned that the proposed PCA-LWSVM model is hard to visualise. Another limitation is the range of training parameters C and Gamma. Higher values of these parameters can be used based on the data characteristics.

The obtained results can be further applied as a post-AOI procedure on the PCB automated assembly line. The proposed method helps manufacturers efficiently classify and manage defects in an automated optical inspection system in the surface-mount technology (SMT) line. The study is particularly useful for the automation of the quality control process since the manual retest of the wrongly classified products would be required no more.

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Dynamics of pertinent project delay variables in the Thai construction sector: mathematical analysis

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ABSTRACT
Project completion behind schedule is a struggle for the construction sector, affecting time, cost, and quality. This investigation has been necessitated by the lingering nature of project delay risks despite many extant analyses. This study collated expert opinions from the Thai construction sector on salient construction delay variables and their influence on each other for DEMATEL-SD analysis. The collated data were analysed and found consistent with a Cronbach's alpha of 0.939. Then, the DEMATEL technique was used to establish the influence weight of factors for the System dynamics (SD) analysis. It was discovered that minimising the design error at the preconstruction stage significantly reduces the magnitude of delay. Increasing values of design error and change order increase the rework profile. Besides, the project delivery within the scheduled 232 weeks can be ensured by minimising the threat of design error, design change, change order, rework, productivity problem, and by improving project management. This study adopted a hybrid mathematical system to holistically examine the construction delay risk by comprehensively exploring the dynamics of influencing variables and investigating their impact on the project scheme. The system helps project stakeholders to arrive at an effective decision in overcoming delay risks, thus minimising the cost overrun and improving the project quality.

KEY WORDS
construction delay, DEMATEL analysis, system dynamics, preconstruction, project management

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Introduction

A construction scheme is an entire blueprint of when a project will be executed and the form of execution. The construction schedule, which is the backbone of any thriving construction project management, outlines project timeframes to keep everything on time. Project scheduling is established to keep the project on track, forecast problems, control costs, and enable timely project completion. Unfortunately, despite project scheduling arrange-

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ments, construction projects face the delay risk, which entails serious negative effects like disputes and total abandonment (Lonergan, 2018). Construction delays are a global phenomenon affecting national economies. Delays in construction project delivery, which is one of the biggest problems in construction management, remain a recurring phenomenon common in developed and emerging economies, often occurring from the design stage to the closeout stage (Carvalho et al., 2021; Jayaraman, 2021; Zhang, 2020). This extension in the time scheduled for project completion is usually a major loss to any construction project, and it decreases the country's GDP (Vishal & Myneni, 2021). Delays in construction project schemes result in time overruns leading to excess costs and, in turn, monetary losses. Time overrun, cost overrun, profit reduction, losses for the owner, distrust between the owner and the contractor, disputes between various stakeholders, and the total project abandonment are direct effects of delay (Salhi & Messaoudi, 2021; Anysz, 2019; Ametepey et al., 2017; Hassan et al., 2017). Therefore, time and cost overruns are common consequences of scheme delays (Kusakci et al., 2017; Sha et al., 2017; Khattri et al., 2016; Hamzah et al., 2011; Motaleb & Kishk, 2011; Pourrostam et al., 2011).

Many investigations have been conducted to identify the factors responsible for this monumental problem. For example, Timilsina et al. (2020) investigated delay causes in a Nepalese construction project, and Mizanur et al. (2014) studied the main causes for schedule delays in construction projects in Bangladesh. Al Amri and Perez (2020) investigated the causes of delays and cost overruns in construction projects in Oman. Many other studies focused on causative factors of delays (Ramli et al., 2021; Alsulaiti & Kerbache, 2020; Soumphonphakdy et al., 2020; Sohu et al., 2019; Saxena & Tomar, 2018; Kusakci et al., 2017; Rahman, 2018; Shahsavand et al., 2018; Soliman, 2017; Kesavan et al., 2017; Gonzalez et al., 2014; Hamzah et al., 2011; Motaleb & Kishk, 2011; Fugar & Baah, 2010; etc.). These investigations on construction delays highlighted scores of factors. Nevertheless, despite the identified factors, construction delays remain a persistent issue, buttressing the fact that an effective remedy to this monumental problem goes beyond the identification of factors, and there is a need for advance investigations in mitigating this problem. Therefore, this study aimed to mathematically examine the dynamics of the delay factors and their impact on the entire project time frame to facilitate effective decisions of project stakeholders, thus mitigating the risk of construction delay.

1. Previous studies

The construction sector, which is an integral part of the country's economy, has been characterised by poor project performance due to project delays. A delay refers to the time extension to complete the project (Hamzah et al., 2011; Khaled et al., 2020; Masood et al., 2015). The project time extension is a common challenge and a global phenomenon that affects numerous projects in the construction sector (Kamandang & Casita, 2018; Tosniwal & Vanakudari, 2018; Vetrova et al., 2020; Jordão et al., 2020; Teplická et al., 2021). Construction delays are a common issue affecting the project duration, which is undesirable to project stakeholders (Asmitha, 2019). A project delay risk is associated with several factors relating to project complexities, which increase with the project size. Several such factors have been examined using different methods for ranking them in the order of criticality.

Anysz (2019) identified low productivity as a key factor inhibiting the timely execution of construction projects. Using the mean score analysis, Mydin et al. (2014) concluded that weather conditions, poor site conditions, poor management, incomplete documents, lack of experience, financial problems, contract modifications, delayed approvals, and coordination problems were the causes of delay. Meanwhile, Emuze (2018) used the mean score analysis and highlighted payment delays, slow decision-making by the owner, change orders, poor communication and coordination, and delays in approvals. Improper planning and scheduling, ineffective project control, management and supervision, poor design and delays in design, rework, shortage of skilled labour and difficulties in project financing were indicated by Saxena and Tomar (2018), who used the relative importance index in their analysis of critical causes of delay. As key delay categories particular to Iran, Zarei et al. (2018) named delays related to initial negotiations, delays related to the contracting process, and delays related to the planning process. The construction industry is large and volatile, and delays in construction projects are recognised as the most common, costly, and risky problem. Consequently, causes of delay were investigated by Qaytmas (2020). Insecurity, corruption, contractors' low experience, and poor management are among the leading

causes of project delays in Afghanistan. Khahro and Memon (2018) adopted the relative importance index to conclude that slow material mobilisation, the unreliability of subcontractors, and labour and material shortages were the causes of delays in the construction industry. Given the frequency and severity of project delays, many studies researched the causes behind such problems, focusing on different countries and using different statistical approaches adopted for the factor rankings (Bounthipphasert et al., 2020; Paray & Kumar, 2020; Asegie, 2019; Chijindu, 2018; Nundwe & Mulenga, 2017; Seran et al., 2017; Seboru, 2015; Zen et al., 2008).

This study presents delay factors (Tab. 1) based on opinions of experts from the Thai construction industry and extant investigations on construction delay factors particular to developed and developing economies. The list reveals similarities between factors associated with the Thai construction sector and those frequently mentioned in the existing literature. It is important to note that 27 factors are direct causes (independent variables) of five embedded factors (dependent variables), namely, the design error, design change, change orders, rework, and productivity.

The decision-making process is essential in managing a successful organisation (Anastasiu, 2018). Decisions need to be made at all stages of a construction project, from the beginning, throughout the execution and to closeout stages (Szafranko, 2017). Various decision-making methods are applied in different situations; therefore, management of construction projects entails decision series. Strategy selection and implementation are important phases in the decision-making processes involved in construction projects. The four major approaches to a decision-making process are inductive, deductive, development of a benefit matrix, and marginal analysis (Szafranko, 2015).

These approaches differ from each other and can be used separately, in a sequence, or in conjunction with each other (Jajak et al., 2015). For example, Samani et al. (2012) examined the fuzzy systematic approach (i.e., fuzzy DEMATEL) to construction risk analysis, while Seker et al. (2017) examined the application of the fuzzy DEMATEL method for analysing occupational risks on construction projects. On the other hand, Erdogan et al. (2016) adopted the analytic hierarchy process as a decision-making tool for construction management. Anastaciu (2018) also investigated the decision-making process in construction project management using the ELECTRE I method.

The complexities of a construction project make the project system difficult. Pertinent factors embedded in the implementation process make the construction project extremely complex, causing colossal challenges to the project control and debasing performance. A hierarchical listing of key factors and the cause–effect relationships among them may not be adequate for the holistic investigation of a construction delay.

Having established the influence weight of these factors, it is also important to comprehensively explore the dynamics of these factors to establish their impact on the entire project schedule for effective decision and planning to significantly mitigate the risk of a construction project delay.

According to Yu-jing (2012), system dynamics (SD) modelling is an effective way to improve performance through effective project control. Researchers have been advocating for exploring nonlinear and dynamic complexity issues involved in construction management. For instance, Maryani et al. (2015) examined the SD approach for modelling construction accidents. SD modelling involves the integration of methods, combining network analysis, fuzzy logic analysis, discrete event simulation, and agent-based simulation.

It is used in examining the impact of a complicated contextual condition in project planning and control, effectiveness and performance, strategic management and sustainability (Liu et al., 2019). The SD's role in advancing other decision-making methods to comprehensively explore relationships and dynamics of a system cannot be overemphasised, as it provides grounds for establishing the impact of parameters on a set standard, initiating effective decision-making to enhance better project performance.

It is important to mention that many investigations have contributed to identifying the causes of delay, but the dynamics and impact of the factors have been rarely explored. Many previous studies have been solely based on a statistical approach to ranking factors in the order of criticality. Usually, researchers opt for such statistical tools as the relative importance index, frequency analysis, average index, linear regression and factor analysis.

Therefore, a hybridisation and combination of mathematical decision-making tools to unravel the dynamics and impact of these factors on project schedules have been rarely investigated. Hence, the need for this study, which adopts a novel approach to identifying key delay factors exploring the dynamics

Tab. 1. Key factors affecting construction delay

Independent variable (cause)	Dependent variable (effect)	Country of study	Reference
• Poor communication • Consultant's lack of experience • Technology used	Design error (DE)	Iran, Malaysia, Norway, Portugal	Abbasi et al. (2020), Arantes & Ferreira (2020), Zidane & Andersen (2018), Fuadie et al. (2017), Shamsudeen & Obaju (2016), Najafabadi & Pimplikar (2013), Couto (2012), Love et al. (2012), Suther (1998)
• Shortage of materials • Owner's late decision	Design change (DC)	Egypt, Ethiopia, Iran, Jordan, Malaysia, New Zealand, Nigeria, Norway, Portugal, Saudi Arabia, Turkey, USA	Bassa et al. (2019), Eksander (2018), Zidane & Andersen (2018), Gebrehiwet & Luo (2017), Lessing et al. (2017), Tafazzoli & Shrestha (2017), Suleiman & Luvara (2016), Samarah & Bekr (2016), Arantes et al. (2015), Yana et al. (2018), Memon (2014), Owolabi et al. (2014), Aziz (2013), Najafabadi & Pimplikar (2013), Kazaz et al. (2012), Mirshekarlou (2012), Sun & Meng (2009)
• Lack of sufficient data before the design • Owner's lack of experience • Inadequate planning and scheduling • Mistake in producing design documents • Rigidity of the consultant • Complexity in project design • Owner's change in requirements • Late procurement • Improper construction method used by the contractor • Difficulties in project financing • Change in materials type during the construction • Owner's financial problem • Delayed payment	Change order (CO)	Denmark, Egypt, India, Iran, Jordan, New Zealand, Nigeria, Norway, Finland, Portugal, Thailand, UK, USA	Abbasi et al. (2020), Arantes & Ferreira (2020), Bahra (2019), Jusilla & Lahtinen (2019), Khoso et al. (2019), Mittal & Paul (2018), Shahsavand (2018), Zidane & Andersen (2018), Lessing et al. (2017), Tafazzoli et al. (2017), Samarah & Bekr (2016), Larsen et al. (2016), Alaryan et al. (2014), Aziz (2013), Halwatura & Ranasinghe (2013), Najafabadi & Pimplikar (2013), Al-Hams (2010), Keane et al. (2010), Toor & Ogunlana (2008), Aibinu & Odeyinka (2006), Ahmed et al. (2003)
• Poor supervision • Poor project management	Rework (R)	Egypt, Ethiopia, Iran, Jordan, Portugal	Arantes & Ferreira (2020), Mahamid (2020), Chandrusha & Basha (2017), Enhassi et al. (2017), Gebrehiwet & Luo (2017), Abeku et al. (2016), Mahamid (2016), Samarah & Bekr (2016), Alavifar & Motamedi (2014), Aziz (2013), Love & Smith (2003)
• Frequent equipment breakdown • Shortage of skilled workers • Poor quality of materials • Conflicts between contractors and parties • Workers' absenteeism • Late arrival of materials/equipment • Contractor's lack of experience	Productivity (P)	Belgium, Egypt, India, Iran, Malaysia, New Zealand, Nigeria, Norway, Turkey, UK	Abbasi et al. (2020), Tahir et al. (2019), European Commission (2018), Karthik & Rao (2018), Zidane & Anderson (2018), Lessing et al. (2017), Moradi et al. (2017), Gascuene et al. (2014), Hickson & Ellis (2014), Aziz (2013), Desai & Bhatt (2013), Kazaz et al. (2012), Ameh & Osebo (2011), Sullivan & Harris (1986)

of the factors to investigate their impact on the project scheme using DEMATEL and system dynamics (DEMATEL-SD). DEMATEL, as a decision-making method, is the proposed fundamental method which will be used as input in the SD model build-up.

2. Research methodology

This investigation develops a conceptual framework, hypothesising that construction delay is mainly

caused by five key (direct) factors (or dependent variables), namely, the design error (DE), design change (DC), change order (CO), rework (R) and productivity (P). Each factor is associated with several independent variables (Tab. 1). Interview questions are developed with five delay factors to collect the data for the DEMATEL-SD analysis. The DEMATEL method is then used to establish the influence weight of factors for the SD simulation model to investigate the impact of each factor on the project scheme through the delay factors dynamics.

2.1. Data collection

The five key construction delay factors and their associated items were used to develop the interview questions to collate information for the DEMATEL-SD analysis. The introductory part of the interview requested respondents to provide their background information, including their current organisation, position, and experience in the construction industry. The main part was designed to collate information about the degree of influence between the five delay factors.

The experts (respondents) were asked to rate the degree of influence (the impact) of one factor in respect of the other on a scale from 0 to 4, where 0 represented "no influence" and 4 meant "very high influence" (Kaushik & Somvir, 2015; Si et al., 2018; Hossain et al., 2020). This was done through binary comparison, where one factor was compared to another factor. As an example, one question asked, "What is the degree of influence between factor DE and factor CO". The response with the value of 4 ("very high influence") showed that the factor DE had a tremendous impact on CO in causing construction delays. The designed questionnaire was reviewed by a group of qualified experts to validate its content.

The DEMATEL analysis is not based on the sample size but on expert judgements, drawing on their substantial experience in the industry of concern (Hossain et al., 2020). In this study, data for the analyses were provided by 15 leading experts working in the building construction companies in Bangkok and other provinces of Thailand. This number of experts was considered adequate (Susanty et al., 2019; Kolbel et al., 2017; Mohiuddin et al., 2017; Yadav et al., 2016; Tsai et al., 2016). The experts were project managers, project engineers and experienced operators with a significant level of work experience in large building construction with an average of THB 100 million in capital investment and over 100 operators. They were also involved in several decision-making efforts related to construction delays.

2.2. DEMATEL analysis method

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) analysis was developed to resolve complicated, problematic groups using matrix mixtures (Kakha et al., 2019; Shieh et al., 2010; Wu et al., 2010). Structured models allow for effective evaluation and formulation of cause and effect relationships. They are described as an effective method for designers and decision-makers, especially in the management field (Kaushik & Somvir, 2015). The approach has been widely applied in many areas, such as airline safety management, web advertising, enterprise resource planning, hospital service quality, mobile banking system service, and the auto spare parts industry (Wu & Tsai, 2011; Shieh et al., 2010; Wu et al., 2010). One of the advantages of this method is the ability to visualise the interrelationships between factors and enable the decision-maker to clearly understand which factors have a mutual influence on one another (Si et al., 2018).

2.3. System dynamics modelling approach

The resulting causal diagram of the DEMATEL analysis is used as a basis for the SD modelling analysis. System dynamics (SD) modelling was created at the Massachusetts Institute of Technology (MIT) by computer pioneer Jay Forrester in the mid-1950s for modelling and analysing the behaviour of complex systems in industrial contexts (Boateng et al., 2012). It was designed to help decision-makers learn about the structure and dynamics of complex systems. The system dynamics approach is based on the concept of a causal loop diagram and is effective in modelling processes that involve change over time and the feedback concept (the transmission and receipt of information) (Ogunlana, 2003).

A clear understanding of how system parts interact with one another and how a change in one variable affects the other over time is the core of system dynamics. Each causal link is assigned a polarity, either positive (+) or negative (-), to indicate how a variable impacts on or is impacted by the other over time (Sterman, 2000). Based on Kim (1999,) a positive (+) link indicates that as one variable changes, the next variable changes in the

same direction or $\frac{\partial y}{\partial x} > 0$. A negative (-) link, on the other hand, indicates that as one variable changes, the other changes in the opposite direction or $\frac{\partial y}{\partial x} < 0$. A causal loop can either be reinforcing or balancing based on the number of negative (-) signs. If there are no negative (-) signs or an even number of negative (-) signs, then the loop is reinforcing. Contrary, the loop is balancing if there is an odd number of negative (-) signs. Another central concept of the SD approach is the stock-flow diagram. It is a representation of significant or insignificant accumulations within the system. On the other hand, flows signify the rate of change in the system represented by inflows (which increase the level of the stock) or outflows (which reduce the stock level). The mathematical relationship between stocks and flows is given as Eq. 1.

$$Stock(t) = \int_{to}^{t} [Inflow(s) - Outflow(s)]ds + Stock(t_o) \quad (1)$$

Where t_o is the initial time, $Stock(t_o)$ represents the stock level at the initial time, s indicates the change in the time variable between the initial time and the current time, while $Inflow(s)$ and $Outflow(s)$ represent the information going in and going out of the stock at time s, respectively (Chaker et al., 2015). The initial stock does not have to be positive as it may be negative, null, or positive. A net flow of stock, also known as the derivative of the stock, is defined as some function of variables and constants. Since most of the system is premised on feedback structure, the net flow will depend on the stock. Therefore, a net flow of stock is as shown in Eq. 2.

$$Net\ flow = \frac{dS}{dt} = f(S,t) \quad (2)$$

Where S is the quantity in stock, t is time, and $f(S,t)$ is a function that depends on S and t (Choopojcharoen and Magzari, 2012). This study

3. DEMATEL ANALYSIS RESULTS

Data were collected from experts. Cronbach's alpha (SAS 2007) was adopted to check the internal consistency of the data. It was calculated based on Eq. 3 using MS Excel and the SPSS 23 software, where k is the total number of delay factors, $\sigma_{Y_i}^2$ is the variance variance for the sum of all respondents. The results revealed that the expert judgements used in the DEMATEL-SD analysis are highly reliable, with Cronbach's alpha of 0.939, which is greater than a minimum acceptable value of 0.7 (SAS, 2007).

$$(\alpha) = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k} \sigma_{Y_i}^2}{\sigma_X^2}\right) \quad (3)$$

Among 15 respondents, 73 % were male. The experts worked for contractors, consultants, and clients of building construction projects, respectively representing 47 %, 33 %, and 20 % of total respondents. Furthermore, 40 % of them were engineers, 27 % worked as project managers, 20 % were architects, and 13 % were quantity surveyors in large construction projects. More than 80 % of respondents had at least ten years of work experience in the construction industry and their current organisations. Respondents' work experiences and their roles in construction projects proved their suitability to provide data for the DEMATEL-SD analysis.

The collected data was analysed using DEMATEL and the MATLAB 2019 software. The following analysis results were discerned.

- Step 1: Compute the direct-relation matrix A. The direct-relation matrix A of all 15 experts was calculated, as shown in Eqs. 4 and 5, and Tab. 2.

$$A = [a_{ij}] = \frac{1}{H}\sum_{k=1}^{H} z_{ij}^k \quad (4)$$

$$S = max_{1 \le i \le n} \sum_{j=1}^{n} a_{ij} \quad (5)$$

- Step 2: Normalise the direct relation matrix A. The normalised initial direct-relation matrix D is constructed as shown in Eq. 6 and Tab. 3.

$$D = \frac{A}{S} \quad (6)$$

- Step 3: Compute the total-relation matrix (T). The total-relation matrix T is calculated, as described in Eqs. 7-9 and Tab. 4.

$$T = [t_{ij}]_{nxn} = D(I - D)^{-1} \quad (7)$$

$$R = \left[\left(\sum_{j=1}^{n} t_{ij}\right)\right]_{n \times 1} = [t_i]_{nx1} \quad (8)$$

$$C = \left[\left(\sum_{i=1}^{n} t_{ij}\right)\right]_{1 \times n} = [t_j]_{1xn} \quad (9)$$

Tab. 2. Matrix A calculation

A						SUM
	DE	DC	CO	R	P	
DE	0.0000	2.2667	2.3333	2.4000	2.2000	9.2000
DC	2.333	0.0000	2.0667	2.2000	2.1333	8.7333
CO	2.2667	2.2000	0.0000	2.2667	2.5333	9.2667
R	2.4667	2.3333	2.3333	0.0000	2.3333	9.4666
P	2.1333	2.2667	2.2667	2.4667	0.0000	9.1334
S						9.4666

Tab. 3. Matrix D calculation

D					
	DE	DC	CO	R	P
DE	0	2.2394	0.2465	0.2535	0.2324
DC	0.2465	0	0.2183	0.2324	0.2254
CO	0.2394	0.2324	0	0.2394	0.2676
R	0.2606	0.2465	0.2465	0	0.2465
P	0.2254	0.2254	0.2394	0.2606	0

Tab. 4. Matrix T and the calculation of the sum of rows (R) and the sum of columns (C)

T						Ri
	DE	DC	CO	R	P	
DE	5.4310	5.4966	5.5346	5.6969	5.6188	27.7779
DC	5.4031	5.0831	5.2944	5.4551	5.3883	26.6240
CO	5.6525	5.5199	5.3652	5.7173	5.6705	27.9254
R	5.7624	5.6223	5.6571	5.6210	5.7525	28.4153
P	5.5223	5.3969	5.4389	5.6078	5.3376	27.3035
Ci	27.7713	27.1188	27.2902	28.0981	27.7677	

Tab. 5. Prominence, relation, and the order of influence of construction delay factors

Factors	Prominence (Ri+Ci)	Rank of factors	Relation (Ri-Ci)	Cause/Effect group
Rework (R)	56.5010	1	0.3180	Cause
Design error (DE)	55.5365	2	0.0077	Cause
Change order (CO)	55.2049	3	0.6355	Cause
Productivity (P)	55.0578	4	-0.4630	Effect
Design change (DC)	53.7306	5	-0.4982	Effect

Tab. 6. Total degree to which a factor is influenced by other factors

RANK	FACTOR	VALUE (%)
1	Rework	20.4691
2	Design error	20.1197
3	Change order	19.9995
4	Productivity	19.9463
5	Design change	19.4654

Tab. 7. Matrix F (for $\alpha = 5.5218$)

F					
	DE	DC	CO	R	P
DE	0	0	1	1	1
DC	0	0	0	0	0
CO	1	0	0	1	1
R	1	1	1	1	1
P	1	0	0	1	0

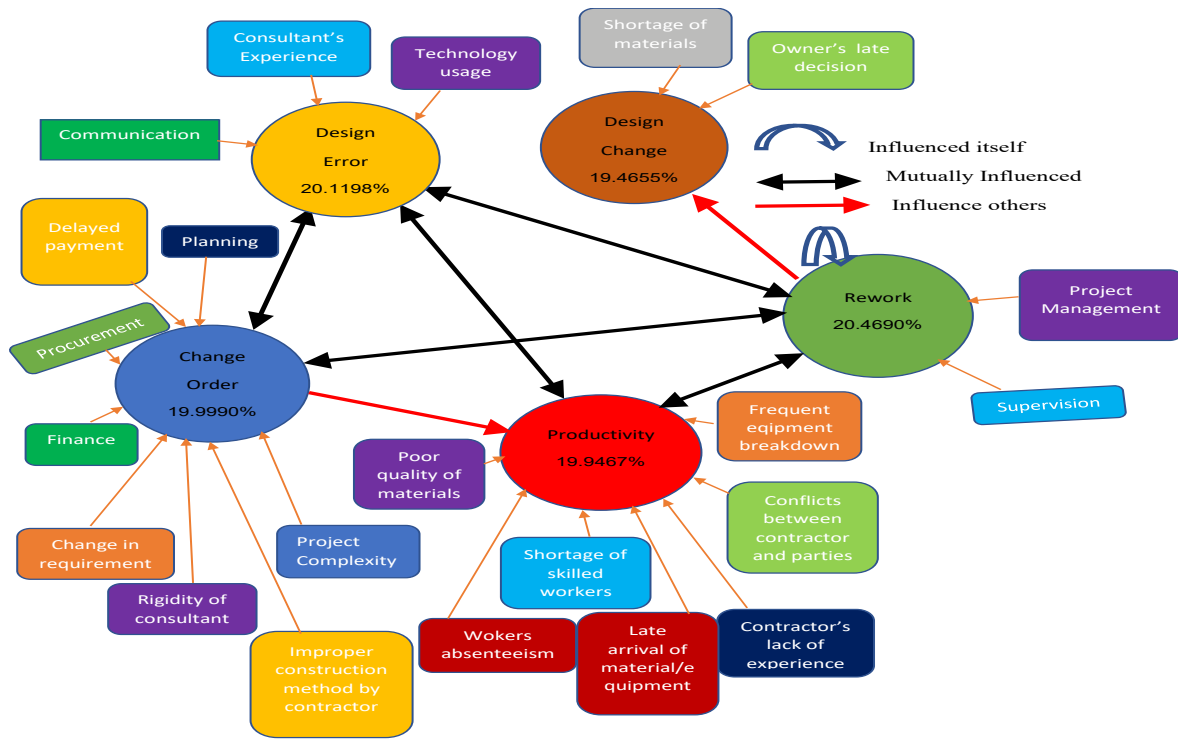

Fig. 1. Summary of DEMATEL analysis results

- Step 4: The prominence and relation of the total-relation matrix T are computed. The vectors (Ri+Ci) and (Ri-Ci) are shown in Tab. 5.
- Step 5: The total degree to which a factor is influenced by the other factor is established by the ratio of each prominence value to the summation of all prominence values (Tab. 6).
- Step 6: Select a threshold value (α) to obtain the diagraph (see Eq. 10). In this study, the threshold value (α) is calculated as

$$\frac{5.4310 + 5.4966 + 5.5346 + \ldots 5.3376}{25} = 5.5218$$

According to Rezahoseini et al. (2019), it is important to form the Matrix F setting element Tij in Table 4 that is equal to or bigger than the threshold (α) of the matrix T to 1 and element Tij in Tab. 4 that is less than the threshold (α) of matrix T to 0. The matrix F for α=5.5218 is calculated, as shown in Tab. 7. The matrix F is used to construct the DEMATEL digraph (Fig. 1). The DEMATEL digraph shows that the design error (DE) factor has a mutual influence with the change order (CO), rework (R) and productivity (P) factors, while the design change (DC) factor is influenced by the rework (R). Rework (R), on the other hand, has a mutual influence with the design error (DE), change order (CO), and productivity (P) factors, and it also influences itself.

$$\alpha = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} [t_{ij}]}{N} \tag{10}$$

4. SD MODELLING RESULTS

4.1. SD MODEL OF CONSTRUCTION DELAY

The five key construction delay factors, the influencing characteristics (Fig. 1) of which were established by the DEMATEL analysis, spanned across the project stages. It is noteworthy that a design error was a problem in the preconstruction stage, according to this study. In a typical design-bid-build system, the design process is completed before the bidding process starts, after which the construction and postconstruction processes commence. The key stakeholders involved in the preconstruction stage were the owner and consultant. The design change, change order, rework, and productivity were problems encountered during subsequent project stages as the contractor was actively involved in this stage with the support of the owner and the consultant to monitor the project. Productivity was also an issue in the postconstruction stage. Therefore, there was a need for proper management and supervision to keep up the productivity to conclude the project on time. The model describing the workflow of the project was established. Fig. 2 describes the workflow of the process (simulation model), while Fig. 3 describes the conceptual model explored to establish the simulation model.

The design process model, which was built on three important concepts, is an embedded and complex system of staff, the productivity in the course of the design process, and their communication overhead. The more people the project involves, the bigger the communication overhead is generated. The design development rate is a function of productivity in design, the number of staff and communication (Eq. 11).

$$Design\ development\ rate = productivity * \\ * \left(1 - \frac{communication}{100}\right) * staff \tag{11}$$

The variable Effective Designers (Eq. 12) depicts the number of full-time, experienced staff that can work on the design. New staff (designers) was believed to have 80 % productivity, subjected to improvement by experienced staff (Suslov & Katalevsky, 2019)

$$Effective\ Designers = 0.8 * New\ Designers + \\ +(Experienced\ Designers - \\ -Experienced\ personnel\ needed\ for\ training) \tag{12}$$

Design tasks were assigned among three different groups of designers with two possible outcomes, i.e., the design was either completed correctly or not, which depended on the error proneness of the designer. The design error proneness by expert designers was given as 10 % of tasks, designers with experience in other projects was 20 % of tasks, and newly recruited designers was 25 % of tasks (Love et al., 2008).

This study considered a design process consisting of 996 requirement units (tasks to be completed). The process scheduled to be completed within 23 weeks (162 days) was a function of several enhancing parameters. The "new designer" and "experienced designer" stocks were associated with two flows representing the rate at which new designers were added and their assimilation. These depended on the number of new designers (staff), as it was hypothesised that the new staff became experienced after 30 days of work. The design process was scheduled to be concluded with a budgeted cost of THB 16,861,960 and an average salary of THB 30,770. Suffice it to mention that the DEMATEL-SD model was applied to an infrastructural project scheduled to be completed within 232 weeks, with 23 weeks for the preconstruction stage, 200 weeks for construction and 9 weeks for closure. The planned project tasks consisted of 10,000 units (Wang et al., 2017). The preconstruction stage consisted of 996 units of tasks, while the construction and postconstruction (closure) stage consisted of 9004 units of tasks.

A group of experts working in leading construction companies in Bangkok and other provinces in Thailand participated in the model validation process. They were top executives, owners, and engineers with

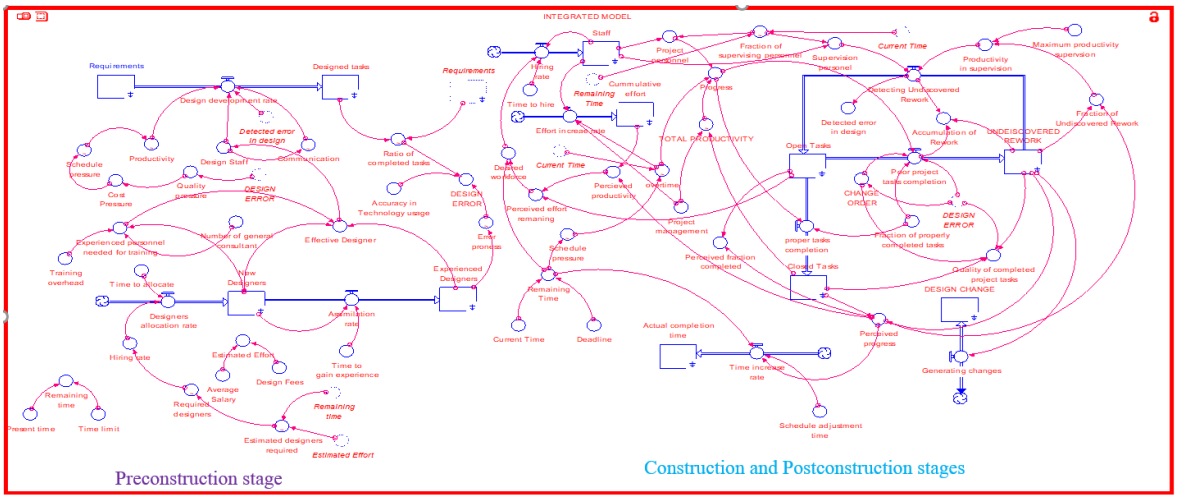

Fig. 2. SD model of construction delay

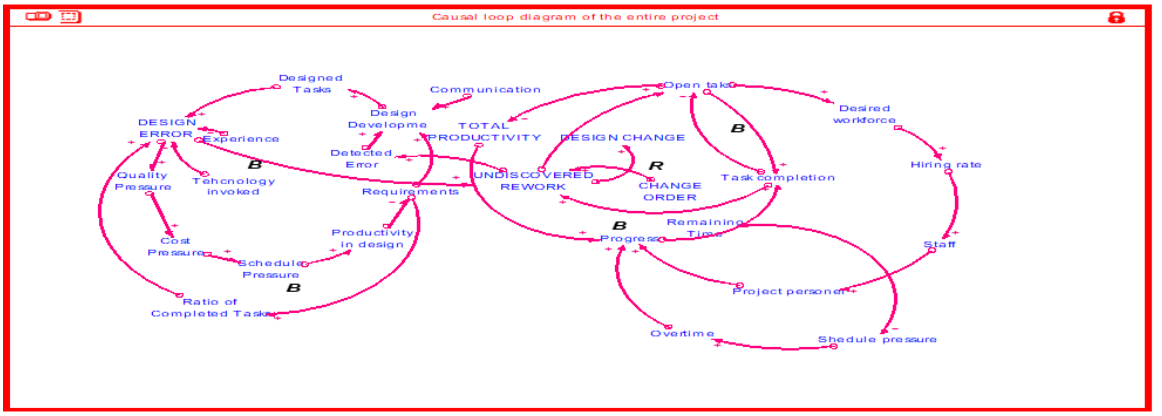

Fig. 3. Causal relationships among key construction delay factors

more than 20 years of work experience in large building construction with an average of THB 100 million in capital investments and over 100 operators. Preliminary information was shared explaining how the model was developed. This helped the experts understand how the model worked. Experts were asked to review the model and suggest improvements. The model was subsequently adjusted based on their recommendations and comments.

4.2. Simulation results

Data from the DEMATEL analysis results are used in the SD model of construction delay (see Tab. 8). Communication, experience, and technology influenced the design error. Design error was, therefore, minimised by these three sub-criteria from 0.2 to 0.0047.

The maximum value of technology accuracy could not be 1 (i.e., 100 %) since human activities could not be 100 % void of error, especially when it comes to the design process, no matter the level of expertise exhibited in handling an advanced engineering design (software) technological system. Even if systems can operate without human intervention, the chance of error still exists (Foord & Gulland, 2006; Busby, 2001). The initial value of design error based on DEMATEL was 0.2, while the minimised value was 0.0047.

Fig. 4 depicts the actual project completion time for different values of the design error. Line 1 (blue) shows the design error at 0.0047, line 2 (red) represents the design error at 0.1, while line 3 (purple) represents the design error at 0.2 (the base value). With the minimised value of the design error (0.0047), the construction process would be completed in the 217th week (and the entire project would be completed in the 240th week).

If the design error is 0.1, it will take 221 weeks to be concluded (amounting to 244 weeks for the entire project). It would take 225 weeks to complete the construction and postconstruction processes if the

Variable	Value	Source
Technology accuracy	0.03-0.07	DEMATEL analysis results
Change order	0.1-0.2	DEMATEL analysis results
Design change	0.194	DEMATEL analysis results
Design error	0.0047-0.2	DEMATEL analysis results
Rework	0.2	DEMATEL analysis results
Project management	0.1	DEMATEL analysis results
New designers	4	Suslov & Katalevsky (2019)
Fraction of properly completed tasks	0.6	Ogano (2016)

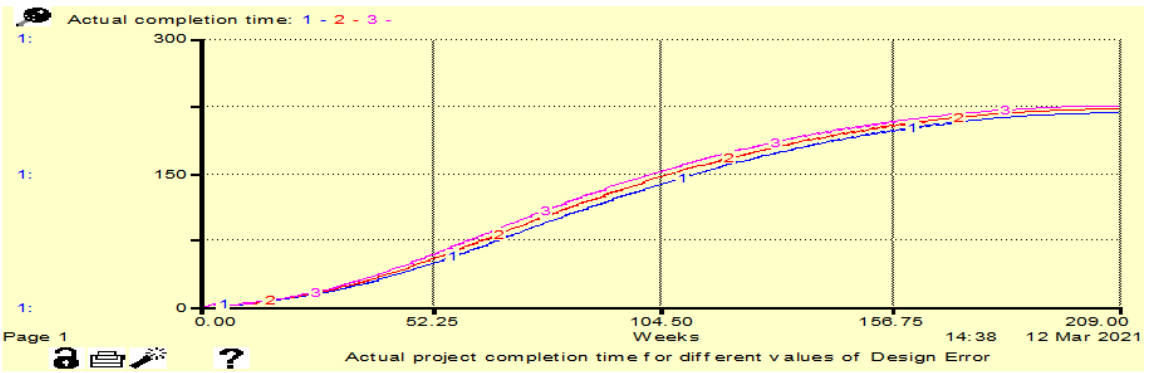

Fig. 4. Actual completion time when Design Error values are 0.0047, 0.1, and 0.2, respectively

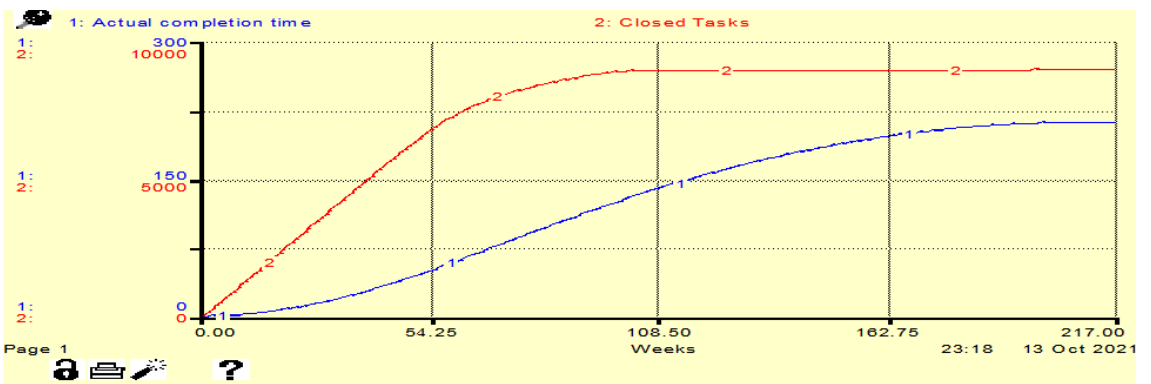

Fig. 5. Actual project completion time versus closed tasks

design error value was 0.2, amounting to 248 weeks for the entire project to be concluded.

Fig. 5 shows that construction and postconstruction are closed at the 217th week (8 weeks later than the stipulated time). This is a justification for minimising the design error, which is a problem of the preconstruction stage. This underscores the fact that construction delays are a risk that originates at an early project stage. Unlike many previous investigations, this study focuses on the need to mitigate the risk of the design error to minimise a project delay. The consultant's role is crucial in ensuring proper supervision of the design process to avoid errors.

The combined effect of the design error and change order on the project schedule contributes to the effect of rework on the project schedule. Based on the DEMATEL digraph of factors, rework is seen as the most prominent factor. The SD model, premised in this scenario as rework, is impacted by the change order, design error and productivity. This makes

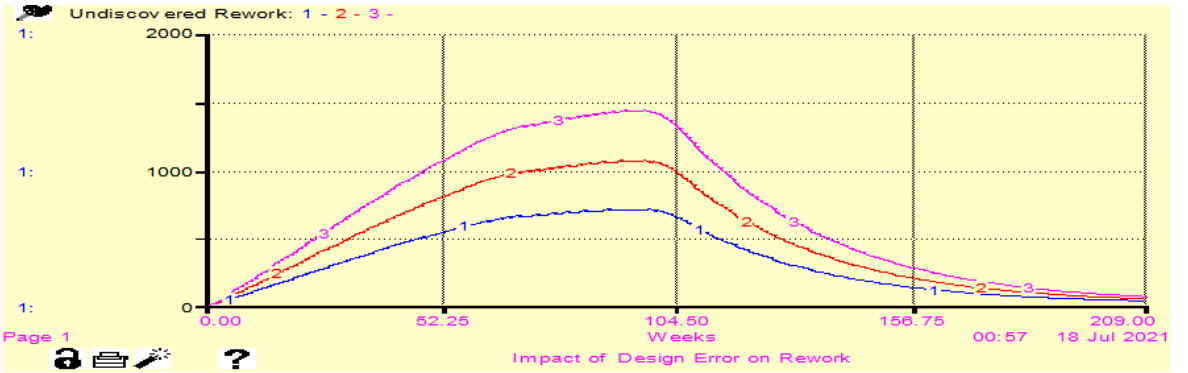

Fig. 6. Impact of the Design Error on Rework when the Design Error values are 0.0047, 0.1, and 0.2, respectively

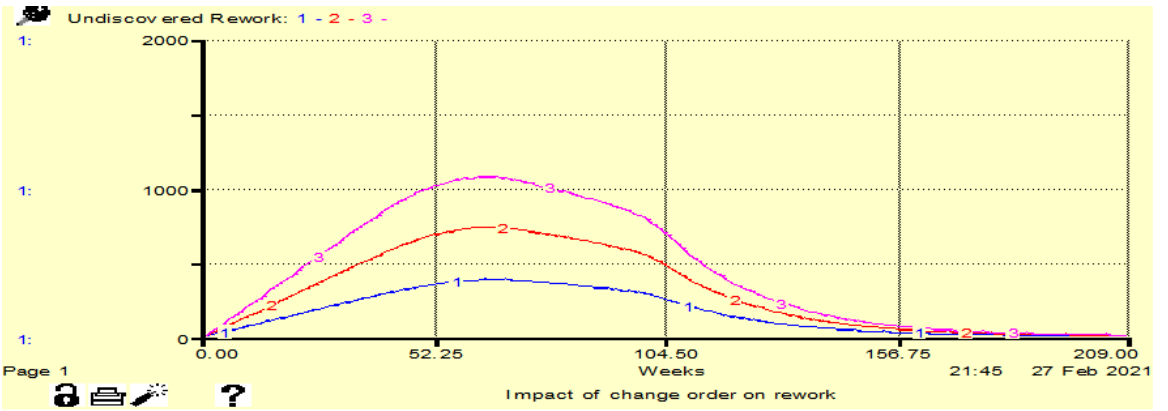

Fig. 7. Impact of the Change Order on Rework when the Change Order values are 0.1, 0.2, and 0.3, respectively

rework a central factor in the model influenced by others as it is described by a stock. Fig. 6 depicts the increasing effect of the design error on rework. Project reworks rise to 1450 units of tasks when the design error is 0.2 (line 3), while rework is minimal when the design error is 0.0047 (line 1). This result explains the linear relationship between the design error and rework, which also corroborates the findings by Love et al. (2008), stating that the design error contributes greatly to the total amount of rework experienced in a construction project which later results in a schedule delay. On the other hand, an increasing value of change order increases the magnitude of rework (Fig. 7). Some changes were made at an early stage of construction, thereby enhancing high rework at the stage, but later, in the course of the project, supervision became more effective, and tasks were completed according to the owner's specification, thereby reducing the threat of rework along the line.

The early stage of construction faces many problems ranging from the design error, change orders, productivity in supervision, the inability of staff to adapt to the construction process on time and others, thereby resulting in many poorly completed tasks which account for a high magnitude of rework even up till the mediate stage of construction. But as the project continues, workers adapt to the work process, and this increases the rate of properly completed tasks and reduces the amount of poorly completed tasks, which, in turn, reduces the rework drastically. This explains the parabolic nature of the rework curve (Fig. 8). The threat of rework was drastically mitigated at the construction stage, thereby leaving the post-construction stage with fewer problems. A serious complication in the post-construction stage would complicate the work cycle and result in a serious project delay. This corroborates the DEMATEL value of rework, showing that rework should be treated seriously and aptly and be made as minimal as possible (say, 0.2) to finish the construction project on time. Fig. 8 shows the rework, closed tasks, and completion time profiles under the combined influence of design error, change order, and productivity.

Fig. 9 depicts the rework profile versus cumulative effort and the actual completion time. The cumulative effort steadily increases throughout the construction process, necessitating a timely clamp-

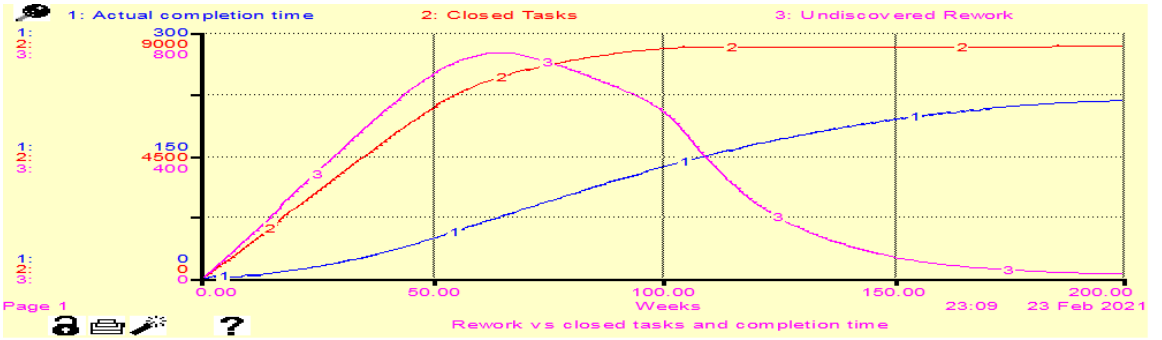

Fig. 8. Relationships among Rework, closed tasks, and completion time

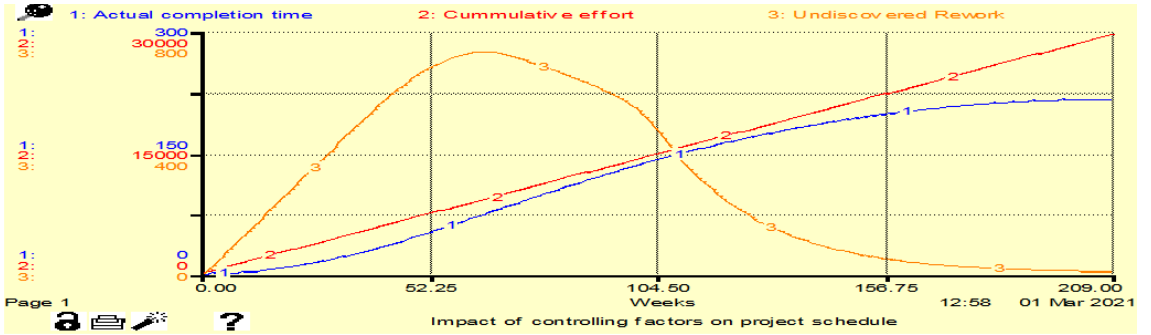

Fig. 9. Actual completion time with the cumulative effort and undiscovered rework

down of rework to ensure the whole process is concluded on time.

Usually, the postconstruction stage is not given the needed attention by project stakeholders, which makes the project suffer delays even at this stage. Therefore, closing more tasks at this stage demands improved productivity. So far, the dynamics of the delay factors and their impact on the project schedule have been examined. Construction delays are minimised, especially with the mitigation of design error and a minimal base value of the change order, which debase the threat of rework and allow for improved productivity. Even under such circumstances, it took 240 weeks to close the project instead of the initially planned 232 weeks, though it could have taken 248 weeks to conclude it, which is much later than scheduled. This analysis is based on the default value of project management of 0.1. According to Ogano (2016), project management can be improved for better project performance in terms of time, say $P \leq 1$. According to this study, project management is a factor associated with rework and based on the prominence value of rework of 0.57, project management is bound and can take a value within 0 and 0.57, which is still less than unity. The studied construction project could be completed within the budgeted 232 weeks if a better project management system was adopted (say P=0.53). It would require a magnificent level of expertise and commitment from the consultant to achieve this.

Fig. 11 depicts the actual completion time profiles for different levels of project management from 0.1 to 0.53. The construction project is concluded in the 232nd week as scheduled, with the project management value of 0.53. The lower the value of project management, the greater the time lag in completing the project. Hence the need for careful consideration of the prominent delay variables hinged on improved project management for timely delivery of a construction project. Project management is crucial in determining the project progress during construction (Ogano, 2016). Procurement and construction are considered the major stages of project management. The procurement system determines the availability of quality materials, their effective use, and the facilitation of reliable and robust construction processes (Matheu, 2005). Effective project management ensures that project members are assigned to specific tasks and that effective monitoring of project progress is performed (Purdue University, 2021). The results, as shown in Fig. 11, prove that an increasing value of project management reduces the project time lag. With better project management, tasks are assigned to project stakeholders without bias and prejudice, thus allowing for effective monitoring of the work progress and, finally, reducing the construction delay.

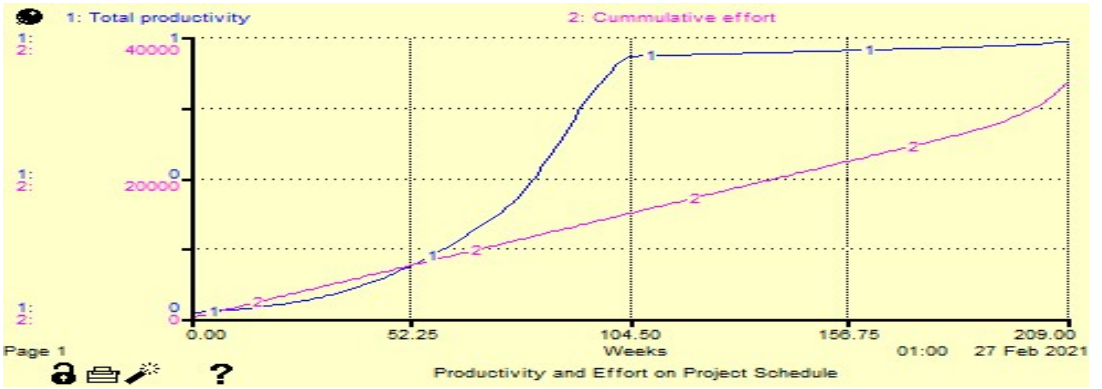

Fig. 10 Total productivity with the cumulative effort

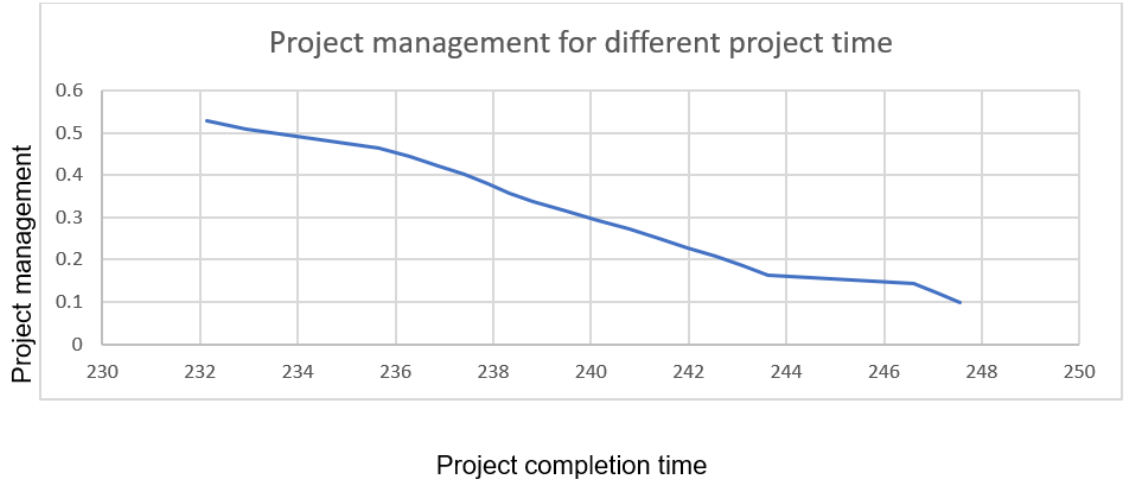

Fig. 11. Actual completion time for different values of project management

5. Discussion of the results

This study adopted the system dynamics modelling to explore the dynamics of factors and the impact of the controlling factors on the project schedule. Effective communication, experience, and better technology are used to reduce the magnitude of the design error. This explains the importance of technology use and communication flows among staff and experience in the design process. The existing advanced design software demands a high level of expertise and experience in applying it to project designs. Effective engineering design software is crucial in modern construction work. Rhino 3D, Revit Architecture, Sketchup, V-Ray, ArchiCAD, Grasshopper, Dynamo, and Fusion 360 are examples of such design software (Archistar, 2020). The performance and accuracy of the design process depend on the effectiveness of handling this software. Some of it is standalone (i.e., it can be used independently), while some must be integrated with other software for better performance. For example, V-Ray can be integrated with ArchiCAD and Sketchup to enhance design processes (Archistar, 2020). In this study, the use of standalone software corresponds to a technology accuracy of 0.03, and the integration of two or more pieces of software corresponds to higher values of the technology accuracy. Therefore, it is important that designers undergo training in design technology to ensure the effective use and enhance design accuracy. Technical know-how (i.e., technology use) and experience are interrelated must be enhanced to mitigate errors. It is, therefore, noteworthy that as companies invest in project design technologies, it is also important to invest in designer capabilities to achieve better project performance and minimise delays at the beginning of the projects.

The design error has a direct relationship with rework, thereby contributing significantly to a schedule delay. Whenever there is an adjustment in design during construction, some completed tasks might need to be redone, which enhances rework in the process. On the other hand, change order varies

directly as rework (increasing the value of change order increases the value of rework), changes during construction alter the initial scope of work, and this modification or alterations necessitates reworks as some completed tasks must be redone. Therefore, it is imperative for project stakeholders to ensure that project scope and requirements are clearly spelt out at the early stage of the project to avoid or mitigate the threat of change order during construction. The impact of the design error on the entire project schedule was examined.

The project ended in the 240th week with the minimised value design error. It could have taken longer to close the project if the design error was not minimised at the preconstruction stage. In addition, closing more tasks demands a high level of productivity as an enhancement for the timely completion of the project. The design process was completed with an error as low as 0.0047, which is less than the initial value established by DEMATEL, signifying that for a project design to be classified as a design with a reasonable level of accuracy, the design error quantity should not be greater than 0.2 (i.e., Design Error ≤0.2) or else the project will suffer serious delays because the design is error bound and characterised by a colossal inaccuracy.

The project extension would be longer if the error in the design is greater than 0.2, as many tasks would have to be reworked. This underscores the importance of the design process with a reasonable level of accuracy. A similar policy applies to change order, as explained by the impact of a change order on rework. The change order has a direct relationship with the actual completion time through rework. The more changes made during construction, the more the rework, which affects the project completion time. The total productivity is modelled to depend on project management as the productivity problem is also a management issue (Rojas & Aramvareekul, 2003; Ogano, 2016).

The project converges with a productivity of 0.8, as shown in Fig. 10. This agrees with the conclusion by Ogano (2016), stressing that a project can be almost concluded with a productivity of around 80 %, a productivity of 20% at 0% of remaining tasks. This also validates the result established by DEMATEL, attributing an influence weight of 0.199 to productivity. The project can be delivered at the stipulated time by carefully considering the pertinent delay factors accompanied by improvement in project management.

Conclusions

This study adopted a novel approach to the analysis of construction delay risks. DEMATEL-SD was adopted to investigate the dynamics of the controlling factors of delay. The hybrid system demands to collect expert opinions on the level of influence of one factor on the other via a binary comparison for the DEMATEL-SD analysis. A conclusion can be drawn that minimising the risk of design error, design change, change order and rework minimises the schedule delay. Therefore, project stakeholders should work consistently to mitigate the threat of these controlling parameters to facilitate improved productivity and minimise the problem of delay.

Companies should give adequate attention to the design process to ensure the project design is void of colossal errors. Consequently, they should invest more in technology, select experienced design teams and encourage effective communication to easily minimise the magnitude of rework and changes during construction as a pathway to improving productivity and quality. Also, good quality of project management is imperative as it enhances timely detection of rework and improves productivity.

This study contributes to the body of knowledge through the uses of DEMATEL-SD to analyse the problem of construction delay and the SD modelling to show the dynamics of delay-controlling factors. The SD analysis is divulged in this study as a reliable mathematical decision criteria method to advance the DEMATEL technique, which underscores the fact that the DEMATEL analysis is a reliable tool to initiate other decision-making methods, especially when there is a need to adopt a hybrid system. The project design process and outcome are key determinants of the overall project performance.

Therefore, the project owner and consultant must work together effectively to achieve a reasonable level of accuracy in the project design and avert problem-bound construction and postconstruction processes. This study helps decision-makers to better understand the complexities involved in construction projects through the comprehensive dynamics of delay factors as a modus operandi to alleviate construction delay. The dynamic model can be modified and used as an effective tool to capture and proffer solutions to several other besetting problems in the construction sector.

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Mathematical model prototype to optimise engineering management of the construction site

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ABSTRACT
Modern construction technologies strongly affect the environment. Therefore, design and building construction should also follow the sustainable development principle. In this case, design and construction work based on the sustainable development principle should aim at creating a safe and healthy living environment, the economical use of natural resources, and the stimulation of economic development to create the welfare for humans and favourable natural conditions. The article proposes a mathematical algorithm as a comprehensive solution for engineering management of the planning construction site, from the calculation of the earthworks to the automated creation of the engineering geological cross-sections. The paper integrates engineering management, mathematical modelling, and BIM technology. The application of the building information model is undoubtedly one of the most advanced technologies used in the engineering management field, whose advantages have been shown by researchers. In the preliminary stage of construction and production management, decisions should be made regarding material and human resources, schedules, and estimates. The main purpose of this article is the optimisation of the excavation. Other issues important to the organisation and management of the construction are the planning of safe work on the construction site, depending on the soil type. Geotechnical sections allow ascertaining the need for additional fortifications and the depth of the fortifications for safe work. The paper describes the principal mathematical model developed by the authors to design a construction site using BIM technologies. It presents the main formulas of a mathematical algorithm aimed at selecting the objects used on the building site and the need for them. It also gives the main principles of engineering management and methods for selecting the mechanisms used on the construction site. Understandably, a specialist's visit to the construction site will not be avoided, and it is difficult to present the entire current situation only with a review report or photographs. Using a photogrammetric model, the expert has the opportunity not only to visually evaluate the current condition but also to perform measurements (length, width, and volume) directly in the photogrammetric model. Important and new information about the construction site indicates all relevant obstacles, i.e., plants, surrounding constructions, and other objects.

KEY WORDS
BIM, building information modelling, engineering management, building site planning, building site management

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Introduction

A construction project is a complex process that requires not only specific knowledge but also managerial skills. Therefore, engineering management and technology management are especially important factors for proper planning and management of a construction project. One of the main problems in the organisation of construction activities is the inefficient planning of construction execution, which increases the cost of construction, prolongs construc-

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tion work execution time, and irrational use of construction machinery and building materials. Construction is one of the first conscious activities of humankind, born from the original human security needs. In its first manifestations, construction was a rather primitive integral process that united three components: thought, means, and action. From today's perspective, these are different components that can already be seen as the beginning of individual stages: the idea, planning, design, measures and actions — construction works. Later, as humanity evolved, construction processes became more complex, forming aesthetics and style. The need for specific knowledge and qualifications separated the individual activities, giving rise to such concepts as "architect", "engineer", etc. The most impressive transformation occurred when simple activities became science and art. As a result of this process, construction (in the general sense) was broken down into a sequence of independent processes with different actors. Today, this sequence is known as an extended concept of the life cycle of a building (project) that begins with the idea of the building and ends with its demolition.

When engineering management is performed, and the construction site is planned, all the factors and risks that may arise in construction management must be considered. It is well known that using the BIM methodology, a building is built twice: first, virtually, and then physically. An analysis of foreign scientific literature revealed that in German-speaking countries, the preparation for construction is separated into an individual stage of construction project management, while in English-speaking countries, it is decided just before the construction or during the construction stage. Of course, the stage selected for addressing the issues of preparation for construction depends on the model implemented by the construction project. Therefore, the earlier the relevant decisions are made, the less costly will be the changes in the future, both in terms of time and money.

Next, in a brief discussion, the authors consider the structure of information system prototyping. It is assumed that the current situation is captured by virtual reality technologies. Tools are currently being developed to capture the current situation using photogrammetry and laser scanning. Using the scanned model further, it is necessary to convert the resulting model to a parametric model. At this stage, no effective solution has been found to automate it. Manual conversion of point cloud to the BIM model is currently available. To effectively plan a construction site, it is necessary to know vacant sites, locations unavailable for machinery installation, the building of temporary roads or designing temporary infrastructure. Currently, this can only be achieved manually, i.e., simply rendered in 3D space, considering the competence of the draftsperson.

One of the most important problems at this point is that current software solutions cannot fully resolve the question of planning construction sites. As shown in Fig. 1, there are still plenty of manual steps to complete the construction-site design process.

Digital technology can have a significant impact on construction management processes. The advantages of BIM technologies for designers are optimised design solutions using the variant design method, improving the quality of the projects and reducing

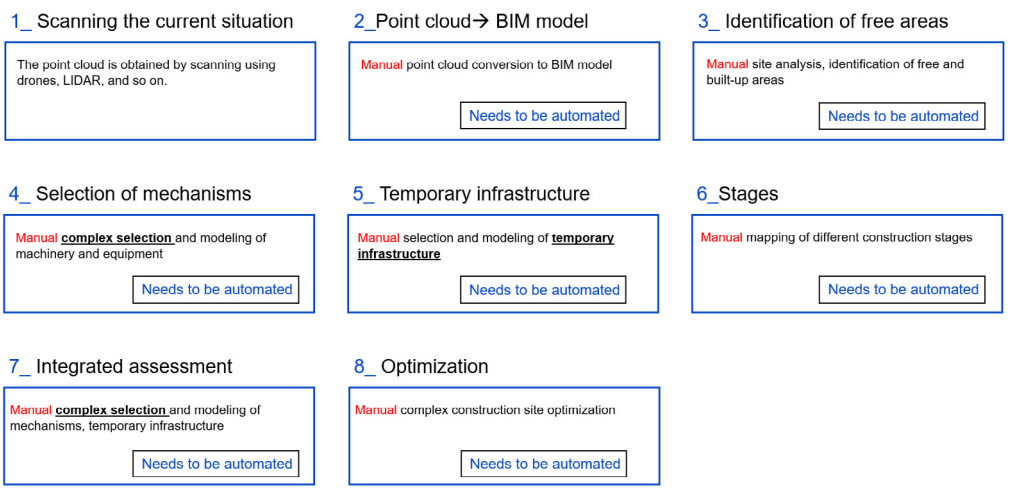

Fig. 1. Information system prototyping structure

labour costs. In engineering production, BIM technologies made it possible to introduce a unique industrial construction, whereas previously, industrial housing construction was associated only with type series and catalogues of standardised products. During the construction management phase, BIM technologies affect the following activities: work planning and management; supply of materials, equipment, and components; performance construction and installation works; carrying out acceptance events; and documentation of works. However, before planning any construction work, it is necessary to carry out the earthworks. The earthworks analysis is useful not only for the design of a building and the calculation of structures, but the results of the earthworks analysis are also extremely beneficial for planning the organisation of construction works.

1. Brief review of the literature and software

Many BIM-related scientific articles and conferences discuss a common data environment, cooperation between project participants, and building modelling. As known, the greatest impact on the investment can be made at its earlier stage. Therefore, the design of a building begins with an analysis of the existing situation, which is very important not only for foundation design but also for construction management planning. Therefore, when analysing the topic of the present article, all articles that somehow analyse BIM and geotechnics were considered. The extensive analysis showed currently no available suggestions for a comprehensive solution for visualisation, design, and optimisation of soil calculation. With a certain solution, engineering management is less risky. Thus, the balance is between three topics of scientific articles that analyse BIM integrity and geotechnics, visualisation, case study, and optimisation. The ways of visualising the land vary depending on the designer's software tools. It is possible with Autodesk Products to successfully visualise soil layers, for example, as indicated in several articles. The efficient three-dimensional visual expression of survey data can not only weigh the scheme scientifically but also make decision-making convenient, simple and efficient. The 3D virtual terrain environment is modelled based on Autodesk Civil 3D and used to assist the geotechnical engineering survey and design. Engineers can view the geological structure data more accurately and intuitively in the real 3D environment, making the design scheme more effective and reasonable (Bai et al., 2021; Berner et al., 2016; Fadoul et al., 2018). There are also solutions in the literature to optimise not only the relevant work related to soil design but also representing a construction site with pairs of simple polygons — demand and supply areas — fully contained in it. The tasks in the articles are different, from the selection and the location of cranes on-site in a cost-minimal way to the systematic exploration of capabilities of virtual prototyping to assist designers in focusing on detailed elements of design optimisation, such as connections, geometry, weight, etc. The assessment also incorporates the importance of part minimisation, standardisation, waste reduction, efficiency improvement, and reduction of on-site operations, machines, and workers (Briskorn et al., 2019; Gbadamosi et al., 2019; Jing et al., 2021; Mahmoudi et al., 2021; Xu et al., 2020). However, no solution was found that would include, for example, calculation, visualisation, and optimisation. Another topic that appears more and more frequently in scientific articles is a case study. The preload analysis process model created by Civil3D can consider uneven settlement during the stacking period in a large-scale site to obtain accurate stacking and unloading engineering quantities (Jian, 2021). BIM has become an important tool for creating a detailed process of building the geotechnical database and the informative geotechnical model, and the geotechnical data. The result of the analysed article (Zhang, 2018) shows that the geotechnical data archived with the proposed strategy can be integrated into the BIM model to form a complete BIM model, which can make decisions and maximise the past investment in geotechnical data. Others present (Wei et al., 2021) the support of BIM software at home and abroad for the scope of application of the BIM model calculation method in the field of landslide control and risk as not enough to completely restore the complicated field situation, but not fully checked in the field of geology. In addition, the focus now is on the combination of geological 3D modelling and BIM with the intention to display BIM projects in the geological surroundings, which is used similarly to a traditional site investigation. Geotechnical data gathered as construction proceeds can be implemented, so the geological and geotechnical situation can be displayed in context. Geotechnical 3D models, which are parallel and based on the geological model, are also used. In them, geotechnical units (rock mass types) are modelled as volume blocks and linked with geotechnical parameter sets (Cudrigh et al., 2018).

In contrast to BIM technologies, which are used to create digital terrain models and building structures in the field of engineering and geological surveys, up to now, the collection and processing of research data have been carried out manually with a presentation in the form of reports on paper or, at best, in digital form in ASCII and XLS formats. Simultaneously, the results of soil stratigraphy determination are presented in JPEG, BMP, etc., in the form of lithological columns and two- or three-dimensional cuts. Among the programs most used by geotechnical engineers are GEO5, PLAXIS, STIMAN, etc. Note that in programs for graphical construction of a two- or three-dimensional geological model, AutoCAD, MicroStation, and NanoCAD are used. All these and other known programs focus on storing data from engineering-geological and geotechnical studies and their processing. An analysis of the programs for geologists noted above shows that they all have the following disadvantages: (1) field and laboratory test data are entered into test data interpretation programs manually into the appropriate tables or via Excel, (2) the absence of a procedure for automatically determining the soils characteristics from geological and geotechnical studies necessary for calculation of bases using analytical decisions, (3) the lack of procedure for determining parameters for soil models from geological and geotechnical research required to calculate the stress–strain state of foundations using numerical methods, (4) the lack of connection between geological and geotechnical studies and programs for calculating foundations for limit states, (5) the lack of assessment of the heterogeneity of a natural soil massif and its influence on the behavior of construction objects, (6) traditional representation of a three-dimensional model in the form of soil layers, and not in the form of a digital field of soil characteristics, and (7) the presentation of research data in the form of a paper report in docx or pdf formats. However, a more significant drawback is the impossibility of transferring data from geotechnical surveys in digital form from the geological programs noted above into geotechnical programs. Geotechnical level programs, e.g., Flac, Z-soil, MidasGTS, etc., perform the calculation using the data from engineering, geological, and geotechnical studies. Usually, solving various engineering problems in geotechnical programs is associated with manual input of soil characteristics directly into programs or using the appropriate procedure of a specific finite element program.

2. Main purpose and methodology

The main task of geological and geotechnical engineering research is to create a computational geomechanical model that will help in engineering management. Traditionally, a geomechanical model is a three-dimensional soil mass consisting of various engineering geological elements and a set of normative and design geological models. It is necessary to carry out the following work: (1) an analysis of engineering and geological surveys of previous years, (2) the determination of the name of soils according to static sounding data and building a lithological column, (3) a complex of laboratory and field studies of soil properties, and (4) 2D or 3D digital imaging of soil characteristics. One of the existing problems is the definition of the boundaries of engineering–geological elements, which are often subjectively found by a geotechnical engineer, especially in the presence of lenses or wedging of soil layers.

To increase the accuracy of the geological layers and boundaries, a digital model of soil characteristics should be developed. Then, the available completed information allows a broad and accurate analysis of

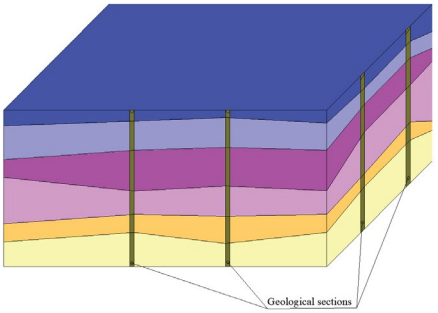

Fig. 2. Geological sections

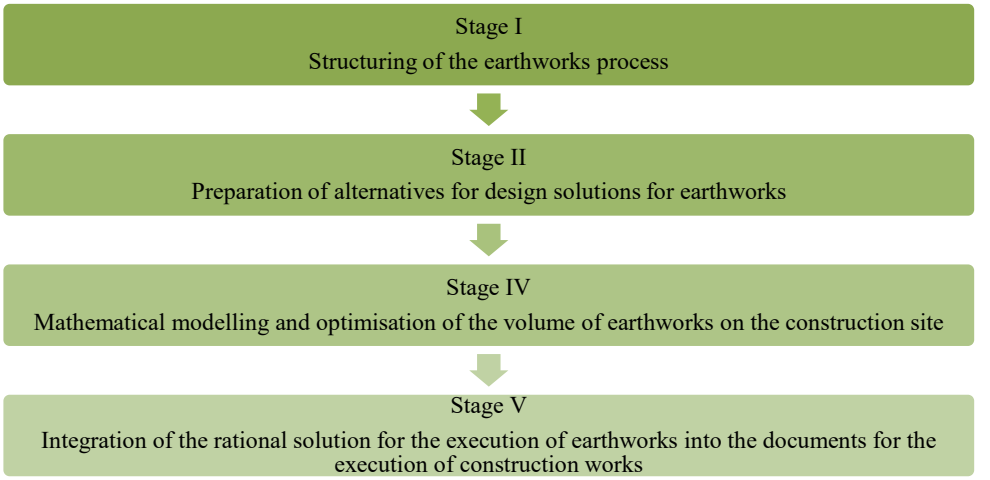

Fig. 3. Rational design solutions for the performance of earthworks

the soil. In the construction engineering preparation system, rational design solutions for the performance of the earthworks are prepared in the following stages.

3. Mathematical modelling and optimisation of earthworks on the construction site

A project made with BIM technology is built twice, once virtually and then physically. BIM technology and principles apply not only to buildings but also to all construction-related processes, including the calculation of earthworks. Therefore, it is vital to fully analyse the current situation in advance and perform a simulation of the planned works. When planning construction work, one of the most important advantages of BIM technology is the calculation of earthworks. This section presents mathematical modelling and optimisation of the volume of earthworks, which are necessary for the designer to develop a construction organisation project, during which engineering and production management are planned. The average range of ground movement is determined by the designers to calculate the labour costs for the execution of earthworks according to the vertical layout, choose a set of earth-moving vehicles and estimate their costs. An analysis of the works allowed concluding that no relationship has been established between the volume of soil and the range of its movement from the slopes of the projected site. Therefore, the study focuses on the influence of the slopes of the construction site on the volume of the soil and the range of its movement. Converting the natural terrain into an easy-to-build view is carried out vertically on the site layout. Experience has shown that when planning work, due attention is often unpaid to the preservation of the vegetation layer, which must be cut off and saved for reclamation of disturbed relief areas before starting site planning work.

Construction site planning can be carried out at a given planning level or with a zero balance of the earth masses. To drain the atmospheric water, slopes are attached to the construction site. When developing documentation for the vertical layout of the site slopes, they are set intuitively, based on the designer's experience. To study the effect of construction slopes on the volumes of earth masses and their distance, the movement was taken on a platform measuring 120 by 160 m, which is divided into squares with a side of 40 m. In the study, 46 options for various slopes were considered. A site without slopes (horizontal) was taken as an assessment option. The calculated results obtained as volumes of earthen masses (V_i,m^3) and distances of soil movement (L_i, m) are expressed in relative values, i.e., the percentage of the volume of earth masses (P_v) and the range of their displacement (P_L) on a horizontal platform. The conducted studies of changes in the volume of earth masses and the distance of their movement from the slope construction sites showed that the slope of the site, the volume of earth masses, and the range of movement of the soil were in a functional relation-

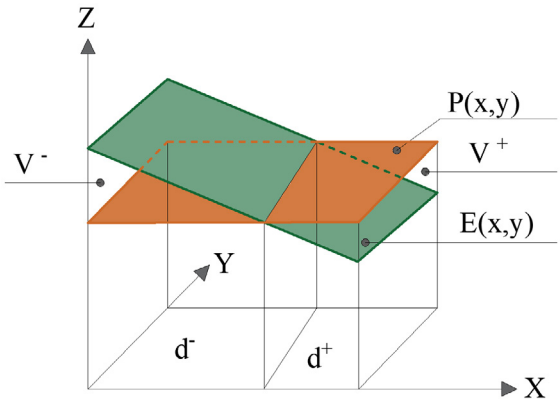

Fig. 4. Layout scheme for an elementary site

ship. For example, when the slope along the Y-axis changes from plus 4 % to negative, the difference in the volumes of earth masses reaches 52 % and the distance of ground movement changes by 26.3 %. The method of determining the volume of earth masses is based on finding the volume of an elementary site, the planned site, enclosed between the surface of the relief and the planned plane. Fig. 4 shows the layout diagram of the elementary section.

The construction site can be tied to an arbitrary coordinate system and divided into elementary sections, at the vertices of which you can define the z_1 and z marks. The boundary of the relief surface in each elementary section is sufficiently smooth and is described by a polynomial of the second order: $z_{1i} = ax^2(y^2) + bx(y) + c, i = \overline{1,4}$, then the existing surface can be represented as $E(x,y)$. The projected surface in each elementary section is a plane whose boundaries of which are straight lines $z_i = kx(y) + b, i = \overline{1,4}$, and it can be written as $P(x,y)$. The task is then to determine the volume bounded between the projected surface $P(x,y)$ and the existing surface $E(x,y)$. The following cases are possible:

1. if $z > z_1$ at any point in the elementary section, i.e., $P(x,y) - E(x,y) > 0$, then the volume will be "+" (filling).
2. if $z < z_1$ at any point in the elementary section, i.e., $P(x,y) - E(x,y) < 0$, then the volume will be "–" (cutting).
3. if $z > z_1$ in some domain of the elementary section, and in the other $z < z_1$, then there is a transition boundary where $z = z_1$, i.e., $P(x,y) - E(x,y) = 0$.

Surfaces E and P can be defined as the following equations:

$$E = A1x + B1y + C1xy + D1 \quad (1)$$
$$P = Ax + By + Cxy + D \quad (2)$$

Since at the points of intersection of surfaces P = E, it means $A1x + B1y + C1xy + D1 = Ax + By + Cxy + D$ or it can be the same as $(A - A1)x + (B - B1)y + (C - C1)xy + (D - D1) = 0; \{(B - B1) + (C - C1)x\}y = (A1 - A)x + (D1 - D);$

$$y = \frac{(A1 - A)x + (D1 - D)}{(B - B1) + (C - C1)x} \quad (3)$$

This means that the equation of the line has been received, which divides the elementary section into positive and negative areas. The projection onto the XOY plane of the elementary section will be expressed by the area D, limited by straight lines:

1) $\frac{x-x_1}{x_2-x_1} = \frac{y-y_1}{y_2-y_1}$; 3) $\frac{x-x_3}{x_4-x_3} = \frac{y-y_3}{y_4-y_3}$;

2) $\frac{x-x_2}{x_3-x_2} = \frac{y-y_2}{y_3-y_2}$; 4) $\frac{x-x_3}{x_4-x_3} = \frac{y-y_3}{y_4-y_3}$

Or it can also be expressed as:

1) $y = \frac{(y_2-y_1)x-y_2x_1+y_1x_1}{x_2-x_1} + y_1$

2) $y = \frac{(y_3-y_2)x-y_3x_2+y_2x_2}{x_3-x_2} + y_2$

3) $y = \frac{(y_4-y_3)x-y_4x_3+y_3x_3}{x_4-x_3} + y_3$

4) $y = \frac{(y_1-y_4)x-y_1x_4+y_4x_4}{x_1-x_4} + y_4$

from here, $y = k_i x + b_i$, where $k_i = \frac{y_{i+1}-y_i}{x_{i+1}-x_i}$, $b_i = y_i - k_i, i = \overline{1,4}$, if $i > 4$, so $i = 1$. The projected plane $P(x, y)$ can be specified as follows:

1) parallel to the X0Y-axis. Then it takes the following equation form: $Cz + D = 0$, or, by reducing in C, it will be: $z + d = 0$, where $d = z_0$ in the whole definition, the area to be controlled.

2) parallel only the X- and Y-axes. If $P(x, y)$ is parallel to the X-axis, then the plane has the form $By + Cz + D = 0$. If the slope to the Y-axis is specified, then the plane equation takes the form $\pm Iy + z + d = 0$, where $d = z_0$. If $P(x, y)$ is parallel to the Y-axis, then the plane has the form $Ax + Cz + D = 0$. If the slope to the X axis is specified, then the equation of the plane takes the form $\pm Ix + z + d = 0$, where $d = z_0$.

3) the plane has a slope both towards the X-axis and towards the Y-axis. In this case, its equation is $Ax + By + Cz + D = 0$. For given slopes towards the X- and Y-axes, the plane equation takes the form $\pm Ix + \pm Iy + \pm Iz + d = 0$, where $d = z_0$.

Slopes in cases 2 and 3 are assumed to be positive if they are directed to the origin (the accepted coordinate grid of the site), and negative otherwise. The relief surface is specified as a harmonic function, and the projected surface is specified as a plane. Since the functions $E(x, y)$ and $P(x, y)$ are continuous at all points in the region D, the volumes of the earth masses enclosed between these surfaces in the area can be represented by the mathematical model in the form of the difference of these functions $\{E(x, y) - P(x, y)\}$ and are calculated by a double integral in the domain D:

$$V_{fill} = \iint_{D-} \{E(x, y) - P(x, y)\}\, dx\, dy \quad (4)$$

$$V_{cut} = \iint_{D+} \{E(x, y) - P(x, y)\}\, dx\, dy \quad (5)$$

The optimal average elevation of the 0 grading is determined from the equality condition of the volume of the soil massif on the site before and after the grading. The volume of the soil massif on the site by region $S = D_1 + D_2 + \ldots + D_n$ can be calculated double integral:

$$V_{volume} = \iint_{S} E(x, y)\}\, dx\, dy \quad (6)$$

Since the function $E(x, y)$ is continuous on the closure $\bar{S}$ of the domain S, which is connected, then it has point x^0 such ($x^0 \in \bar{S}$) such that the equality $\iint_S E(x, y)\, dx\, dy = E(x^0)mS$, hence the value of the function $E(x, y)$ in the point x^0, $E(x^0) = \frac{\iint_S E(xy)\, dx\, dy}{S}$. Let the virtual plane have a mark z_v from absolute mark ± 0.000. Let us calculate the volume of the soil mass in the region S between the relief function $E(x, y)$ and the virtual plane $P_v(x, y)$. The volume between the surface of the relief and the virtual plane over the region S is then determined from the expression:

$$V_{cut} = \iint_{S} \{E(x, y) - P(x, y)\}\, dx\, dy \quad (7)$$

Therefore, the optimal average mark H_0, based on the equality of volumes: $H_0 = z_v + \frac{V_v}{S}$. Possible design surfaces of a construction site with its vertical layout can be represented as a bunch of planes in a Cartesian coordinate system centred at the point $F\{x_c; y_c\}$, the coordinates of which correspond to *xc* and *yc* — the middle of the area *S* and *z* — plan marks H$_0$. The equation of the beam of planes can be represented in the form $H_0 \pm I_x\, x \pm I_y\, y \pm I_z\, z = 0$ or $F_i(x, y) = H_0 \pm I_{ix}\, x \pm I_{iy}\, y,\ i = 1, \ldots, n.$ Volumes of earth masses between the site relief and such planes:

$$V_S = \iint_{S} \{E(x, y) - F_i(x, y)\}\, dx\, dy = 0, \quad (8)$$

$$i = 1, \ldots, n.$$

Consequently, the statement that the equality of the volumes of embankments and excavations of the planned site meet the optimality conditions is not complete since expression (1) indicates many such situations. Then, the minimising functional of the amount of work on the construction site can be represented as

$$V_S = \iint_{S} \{E(x, y) - F_i(x, y)\}\, dx\, dy \xrightarrow[y \epsilon S+]{x \epsilon S+} min \quad (9)$$

Restrictions:

$$\iint_{S} \{E(x, y) - F_i(x, y)\}\, dx\, dy = 0; \quad (10)$$

$$\iint_{S+} \{E(x, y) - F_i(x, y)\}\, dx\, dy \geq 0; \quad (11)$$

$$F(x,y)\ \epsilon\ H_0 \pm I_{ix}\ x\ \pm\ I_{iy}\ y = I_z\ z); i = 1, \ldots, n; \quad (12)$$

$$H_0 = E(x^0, y^0); x^0\ \epsilon\ S;\ y^0 \epsilon\ S. \quad (13)$$

Therefore, it is possible to optimise the volume of the earthworks in the case of vertical levelling of the site, provided that the ground balance is zero. The optimality criterion is the coincidence of the relief surface and the planning plane. In this case, the optimisation vector of the volume of work is determined under the condition that the slopes of the terrain and the planning plane coincide in value and direction.

The methodology for determining the volume of earth masses, the distance of their movement, and their relationship with the mechanisation of work not only allow determining rational methods for carrying out earthworks at the construction site but also give a breakdown of the work in general, which must be considered when planning earthwork.

Discussion and conclusions

Engineering construction management is one of the most difficult construction processes. The success of the entire project depends on the management of the construction. To plan a proper engineering construction management process, it is necessary to know all the potential risks that may arise during the project. One of the solutions proposed in this article allows for accurate earthworks. The reviewed state of BIM technologies illustrates the importance of incorporating geotechnical survey data into the BIM process. The proposed information technology combines engineering and geological research and design of the foundations of buildings and structures into a single production engineering process and can be used as one of the elements in the composition of digital information systems of buildings and structures. Information modelling technology allows reducing the time and improve the quality of engineering–geological studies due to the automation of laboratory and field soil testing and the determination of soil characteristics with the simultaneous calculation of building foundations and facilities for limit states. The proposed model may have restrictions on its use if soil properties and species are incorrectly determined. Then, the soil optimisation task can be calculated incorrectly, so engineering planning and management would have inaccuracies. But the solution proposed in the article has strengths because the suggested optimisation method is beneficial in many areas, from project planning and project engineering management to specific construction works (foundation installation, etc.).

A literature and software review has shown that tools are currently being developed that calculate the scope of earthworks using BIM models. However, the analysis did not find any complex solutions that would include land type determination, land modelling, earthworks calculation and optimisation. Therefore, this paper presented a mathematical model that optimises earthworks.

This article also aims to invite researchers to further explore the topic of earthwork optimisation using BIM technology. The optimisation algorithm presented in this paper allows for performing further optimisation tasks related to the construction site organisation. This means that once a rational plan for earthworks and soil supply is known, the mechanisms to be used in the soil supply system are further selected. With the rational soil supply plan, the required number of trucks is determined on the construction site. Excavators and trucks are optimised for the purpose of this work: the required number of machines transporting the soil is made available for bringing the soil to the construction site when the soil is excavated with different mechanisms (excavators, loaders, draglines) to keep the total costs of machine downtime the lowest. After receiving a rational design solution for the soil spreading and soil supply plan, the required number of mobile trucks is integrated into the construction work documents (construction work technology project, estimates, work schedules, etc.).

This article examined one of the most important issues related to engineering management, i.e., the optimisation of earthworks. Other important issues for the organisation and management of construction are the planning of safe work on the construction site, depending on the type of soil. Geotechnical sections allow for planning a need for additional fortifications and their depths for safe work.

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Supporting industrial implementation of R&D results with commercialisation models

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A B S T R A C T
The paper aims to present commercialisation models for advanced technologies and services which can be applied in an R&D organisation. Against the background of the literature review on theoretical and practically verified commercialisation models, and marketing strategies and tools, the authors propose an original model, 7MWwBP, composed of several hybrid submodels. The model is intended to support commercialisation processes carried out at R&D organisations. The model is based on the input criteria (the type of innovation and the character of the innovation related to the market demand scale), and it indicates possible commercialisation paths (sale, licence, provision of a service, or a spin-off) and sets of dedicated marketing tools (BTL). The advantage of the model is that an R&D result (innovation) is its focal point, and the whole commercialisation process depends on it. The model aims to mitigate an empirical and research gap as regards commercialisation models suitable for R&D organisations. Furthermore, the model is distinguished by a holistic approach, which is not common for the commercialisation models described in the literature, as they do not comprehensively consider the relationship between the models and the type and character of a technological solution, commercialisation path, and the marketing tools used for commercialisation of R&D results. All the listed aspects are considered and included in the 7MWwBP model, which makes it suitable for the commercialisation of R&D results originating from research organisations, as presented in and substantiated by the example of an actual commercialisation process concerning R&D results in the field of optomechatronics.

K E Y W O R D S
technology management, prototype production and services, R&D organisation, commercialisation models, marketing tools, commercialisation path

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Introduction

The commercialisation of scientific research results is a widely studied subject by academics and the business community (Maktabi & Pazhakh, 2010; Boehm, 2013; Carayannis et al., 2016; Kozien & Kozien, 2017). The process is accompanied by numerous challenges connected with applying innovations in the industry (Kirchberger & Pohl, 2016; Mazurkiewicz et al., 2021). Commercialising scientific research can be difficult in practice because of the steps required to

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turn basic research into practical results (Fletcher & Bourne, 2012). In the case of scientific research results, it also happens that a market for a product is searched for (technology push). This is significantly different from producing a product designed to fit an established or obvious market (market pull).

Numerous models are developed and used to facilitate commercialisation processes. Although such models are a subject of theoretical investigations and practical applications, there is an empirical and research gap concerning commercialisation models suitable for R&D organisations. Furthermore, the commercialisation models described in the literature do not comprehensively consider mutual connections of the models and (1) the type of a technological solution, (2) its character defined by the market demand scale, (3) customised commercialisation paths depending on the type and character of a technological solution, and (4) a proposed set of the marketing tools to be used for the commercialisation of R&D results.

The proposed model comprehensively covers all the aspects. Its application helps mitigate the relatively high risk pertaining to the development and effective practical implementation of innovations, which is possible because of a holistic approach adopted for the model that considers numerous aspects affecting the commercialisation process. The model is split into submodels, which is particularly useful for researchers interested in the commercialisation of R&D results because, depending on the type of a technological solution (material, technology, system, device or service), a customised path is proposed. The advantage of the model is its focus on the R&D result, which, depending on its type, enables the selection of the most recommended submodel.

Thus, the paper attempts to answer the following research question: "What dedicated commercialisation models, designed with the use of the input criteria, i.e., the type of a technological solution and the character of the innovation related to the envisaged market demand scale, can be used at R&D organisations and what commercialisation paths and marketing tools are the most appropriate for these particular models?".

The paper aims to present an original commercialisation model, 7MWwBP, for advanced technologies and services which can be applied in an R&D organisation. The paper is structured as follows: first, it draws on a literature review and discusses the results in two areas: (1) commercialisation models developed by scholars or applied in practice, focused on commercialisation processes carried out by or with the participation of R&D organisations, with particular attention paid to the possible input criteria, stages of the commercialisation process, and commercialisation paths; and (2) marketing strategies and tools. Against the conducted literature review, the authors present the 7MWwBP commercialisation model suitable for an R&D organisation, which considers the input criteria characteristic for individual commercialisation paths and the marketing tools. The presentation of the model is followed by the example of its practical application with regard to innovations in the field of optomechatronics. The paper is summarised with conclusions indicating possible future model development directions.

1. Literature review

The state-of-the-art analysis comprised two areas: (1) commercialisation models, with a particular focus on models designed for or applied in R&D organisations, and (2) marketing tools and strategies. The literature review concerning the commercialisation models and marketing tools was focused on identifying ideas to support the process of designing commercialisation models for R&D organisations.

As a result, the following dedicated models developed for individual R&D organisations or other scientific communities (Table 1) were selected as a background for designing the original 7MWwBP model for an R&D organisation:

- the model using the TTRI_MP method (Jou & Yuan, 2016) to guide technology development, improve NPD decision-making processes, and support the management of new product development and commercialisation;
- the RIPI's New Technology Development Process from Idea to Market (Bandarian, 2007), supporting the staff of research institutes and universities in effective planning of the commercialisation process of technologies;
- the sustainable innovation academic entrepreneurship process model (Qian et al., 2018) concerning the performance of various functions by representatives of the scientific community in the creation of enterprises based on new technologies;
- the Research and Development–Commercialisation Bridge (R&D-C Bridge) model (Budi & Aldianto, 2020), enabling a detailed analysis of the succeeding stages of the successful commer-

Tab. 1. Examples of commercialisation models developed for individual R&D organisations or other scientific communities

MODEL AND AUTHORS	MAIN CHARACTERISTICS	INPUT CRITERIA	STAGES OF THE COMMERCIALISATION PROCESS	COMMERCIALISATION PATHS
TTRI_MP Method, Jou and Yuan, 2016	Facilitating the process of new technologies development and improving the efficiency of implementation in practice	Technology Readiness Level	1. Market exploration and technology forecasting 2. Idea generation and segmentation 3. Portfolio analysis 4. Technology roadmapping	licence, spin-off
RIPI's New Technology Development Process from Idea to Market, Bandarian, 2007	Supporting researchers in effective planning of the commercialisation process of technologies	-	1. Idea 2. Laboratory self-screen 3. Opportunity recognition & conceptual analysis 4. Categorising opportunity types 5. Technology development (technical activities) 6. Looking for & identifying industrial buyers, commercial entities & eager investors 7. Looking for & providing required conditions for field (applied) tests & certificates 8. Carryout field (applied) tests, verification testing, receiving required certificates & intellectual property protection 9. Developing the business concept of technology (commercial feasibility) 10. Contact & connect to industrial buyers, commercial entities & eager investors for explanation 11. Strategic evaluation of technology for finalising 12. Valuation & pricing 13. Commercialisation plan 14. Convincing the eager for the technology & creating a positive belief regarding the benefits of the technology 15. Technology transference and establishing post-launch review & after establishing supports	sale, licence, services
Sustainable innovation academic entrepreneurship process model, Qian et al., 2018	Involvement of the scientific community in entrepreneurial activities; creation of enterprises, and commercialisation of new technologies	The roles played by researchers in the framework of undertaken entrepreneurial activities	1. Idea generation 2. Developing the experimental prototype 3. Deciding to commercialise 4. Creating the product prototypes 5. Creating the new venture 6. Developing the new venture 7. Producing the product 8. Generating sales	licence, sale, spin-off
Research and Development–Commercialisation Bridge model (R&D-C Bridge), Budi and Aldianto, 2020	Commercialisation model, in conjunction with organisations dealing with technology transfer and with tools needed to execute the process of technology commercialisation	Technology Readiness Level Technology Needs Value (TNV), Integration Readiness Level (IRL), Innovation Readiness Diagram (IRD)	1. Research mapping and selection. 2. Technology/ research assessment for commercialisation decision 3. Commercialisation model decision-making 4. Commercialisation process 5. Commercialisation subject selection 6. Commercialisation advising, facilitation, and linking 7. Commercialisation cooperation and synergy 8. Commercialisation coordination model 9. Commercialisation funding and resources 10. Market analysis 11. Technology introduction process 12. Assessment of commercialisation performance	spin-off
Technology-Product-Market (TPM) Model, Minseo et al., 2019	Analysis of commercialisation steps in the context of the assessment of the target market	-	1. Technology development 2. Product development 3. Market	sale

cialisation process while considering the characteristics of the relationship and integration between the institutions involved in different phases of the commercialisation process; and
- the Technology-Product-Market (TPM) model (Minseo et al., 2019), focusing on analysing the succeeding stages of commercialisation in terms of assessing the target market, which provides the tools needed to see how technology and product developments are perceived by potential consumers.

The selected models are analysed with respect to the following: (1) the aspects which, while developing commercialisation models, may be treated as the input criteria, (2) the stages of the commercialisation process, and (3) the commercialisation paths. These aspects are also covered by the set of the 7MWwBP submodels.

Within the analysed models developed by other scholars, products and technologies are distinguished because they require different approaches (Minseo et al., 2019). Considering this, a type of innovation can be treated as an input criterion. Moreover, TRL was most frequently indicated as a possible factor influencing the model. The authors plan to include this aspect as an input criterion at the stage of further development of the 7MWwBP model. However, at first, based on the experience in the development and commercialisation of innovations at an R&D organisation and with the support of experts in this field, the authors decided to consider the input criteria, such as the type of innovation (consistent with state-of-the-art, but more detailed) and the character of innovation related to the possible market demand scale. All models presented in the paper (Table 1) propose the stages of the commercialisation process, and some of them also propose a commercialisation path (sale, provision of a service, licence, or spin-offs).

The analysed commercialisation models do not comprehensively cover marketing activities that could be taken to commercialise innovations effectively. On the other hand, the importance of developing and applying an appropriate marketing strategy for effective commercialisation is unquestionable, especially in the case of functioning in the market of innovations (Robul et al., 2020). The comprehensive matching of marketing tools and selecting appropriate forms of marketing communication are indispensable parts of managing the commercialisation process. It enables R&D organisations to be in constant contact with their existing and potential customers, which directly impacts the effectiveness of commercialisation processes. Thus, the second area of the state-of-the-art analysis comprises marketing strategies and tools for the purpose of a commercialisation process and covers the following (Table 2):
- segmentation models (Kuipers, 2018), referring to the business-to-business environment;
- a strategy for market segmentation and differentiation (Arsova & Temjanovski, 2019), dedicated to targeting consumers;
- marketing strategies for innovations (Kharchuk et al., 2014), highlighting their comprehensive role for companies;
- modern marketing instruments (Tarasova et al., 2020) while considering two types of marketing

Tab. 2. List of examples of marketing models, strategies and tools

Name	Authors	Entity	Thematic scope
Segmentation models	Kuipers, 2018	Companies within B2B	Recognition of segmentation criteria when the customer is a company
Strategy for market segmentation and differentiation	Arsova and Temjanovski, 2019	Companies	Creating and formulating a marketing strategy for companies
Marketing strategies for innovations	Kharchuk et al., 2014	Companies	Analysing the role of strategic marketing towards the development and commercialisation of innovations
Modern marketing instruments	Tarasova et al., 2020	Companies	Modern marketing instruments for the company's market promotion, considering ATL and BTL marketing communication
Marketing tools	Gvozdetskaya et al., 2016	Universities	Marketing support for the commercialisation process of intellectual property items
Digital marketing tools in the value chain of an innovative product	Robul et al., 2020	Companies	Analysis of marketing and innovation activity at the stages of the value chain and the role of digital marketing in the value chain

communication: ATL-communications (direct) and BTL-communications (indirect);
- marketing tools (Gvozdetskaya et al., 2016) used for marketing support of the commercialisation process of intellectual property items; and
- digital marketing tools in the value chain of an innovative product (Robul et al., 2020).

The presented examples refer to different entities, mainly companies, because they have considerable experience in marketing activities. They were selected because R&D organisations should act similarly to enterprises in the area of commercialising innovations. On the basis of the state-of-the-art analysis, marketing tools are proposed for particular 7MWwBP submodels.

The results of the state-of-the-art analysis were used for the following purposes:
- selecting the input criteria for designing 7MWwBP commercialisation submodels;
- designing the set of 7MWwBP commercialisation submodels;
- the recommendation of commercialisation paths; and
- the recommendation of the sets of marketing tools.

The 7MWwBP model comprises the input criteria determining its submodels, for which commercialisation paths and a set of suggested marketing tools are proposed.

2. Method

The scope of the literature review conducted by the authors first comprised all commercialisation models, with particular attention paid to models developed for or applied in R&D organisations, and, secondly, marketing strategies and tools that may support the effective use of the models. As a result of the state-of-the-art analysis, examples of commercialisation models suitable for the commercialisation of R&D results were selected. Although the authors managed to identify commercialisation models meant for R&D organisations, none of them comprehensively consider the relationship between the models and the type of a technological solution, its character related to the market demand scale, commercialisation path depending on the type and character of innovation, and the marketing tools used for the purpose of commercialisation of R&D results.

The state-of-the-art analysis comprised academic literature (mainly including two databases: ISI Web of Science and Scopus) and grey literature (reports, working papers, government documents, white papers). The search in the first area (commercialisation models) used keywords "commercialisation models", "New Product Development", "New Technology Development"; and in the second (marketing strategies and tools), it used such keywords as "market strategy", "marketing tools" and "market segmentation". In total approx. 120 papers were collected in the first area and about 180 papers in the second. All papers were subject to a two-stage analysis. In the first stage, abstracts were read, and whole papers were roughly reviewed. After this stage, approx. 80 papers from the first area and about 45 papers from the second were selected for in-depth analysis. As regards marketing strategies and tools, this is a very rich area with plenty of publications; however, only a small part of them concerns marketing activities related to commercialisation activities. In the second stage, the publications were analysed with respect to (first area) models and methods used for facilitating commercialisation processes at R&D organisations and other scientific communities and (second area) marketing strategies and tools that may support the commercialisation models. As a result, five examples were selected in each area for inclusion in the paper as a background for presenting a commercialisation model, 7MWwBP, developed by the paper's authors.

Against the background of the state-of-the-art analysis and with the consideration of the authors' experience of participation in research and commercialisation projects, a set of seven submodels was proposed for the implementation of research results and products (7MWwBP) developed at an R&D organisation. The authors assumed that different types of R&D results required different commercialisation paths. At first, real technological solutions of each type (i.e., material, technology, system, device and service) were selected and initial commercialisation models were proposed, considering the findings of other scholars and practitioners. Next, these initial models were verified on several dozen examples of commercialised R&D results, which contributed to the further development of the models.

The authors briefly describe the proposed commercialisation models. A particular emphasis is placed on the input criteria which determine each submodel, as well as on the commercialisation paths and marketing tools suggested as the most appropriate for each submodel. The proposed models are currently used in practice by an R&D organisation, the Łukasiewicz Research Network – Institute for

Sustainable Technologies, for the commercialisation of results of various scientific, R&D and implementation activities. The potential practical application of the models is presented using the example of optomechatronic technologies.

3. Results

Based on the literature review, while considering the specific characteristics of R&D organisations, the authors designed a set of seven marketing and business submodels for the implementation of research results and products (7MWwBP). The submodels were built according to the two input criteria, i.e., the type of solution (innovation) and the character of the solution. The following types of solutions were distinguished (Mazurkiewicz et al., 2015):

- services (e.g., IT, surface engineering);
- materials (e.g., chemical, textile, composites);
- systems (e.g., software, computer systems);
- technologies (e.g., chemical, mechatronic); and
- equipment (e.g., research and testing apparatus).

The second criterion concerned the character of the solution related to the market demand scale (Walasik, 2018):

- unit;
- short series; and,
- mass production.

For each model (Fig. 1), possible commercialisation paths and suggested marketing tools were proposed.

Although individual submodels are customised to the type and character of a technological solution, all of them are characterised by the same approach and include the same elements (the proposed main commercialisation path and main marketing tools). They are unified in one 7MWwBP model to present the whole set of approaches to be applied with regard to the possible types of R&D results. Each researcher interested in commercialisation selects a particular submodel suitable for the R&D result. The awareness of other submodels is very useful, especially if R&D results can be practically implemented with the use of different commercialisation paths, e.g., a direct sale of a device to the market or the provision of services by R&D organisations with the use of this designed and manufactured device.

The developed commercialisation models comprise the Innovation Model, the Niche Model, the Sub-supply Model, the Comprehensive Model, the Market Model, the Infrastructure Model, and the Phase Model. The proposed models were described in detail by Poteralska and Walasik (2021). A short summary is offered below.

M1 — Innovation Model is based on gaining and maintaining the technological advantage. Innova-

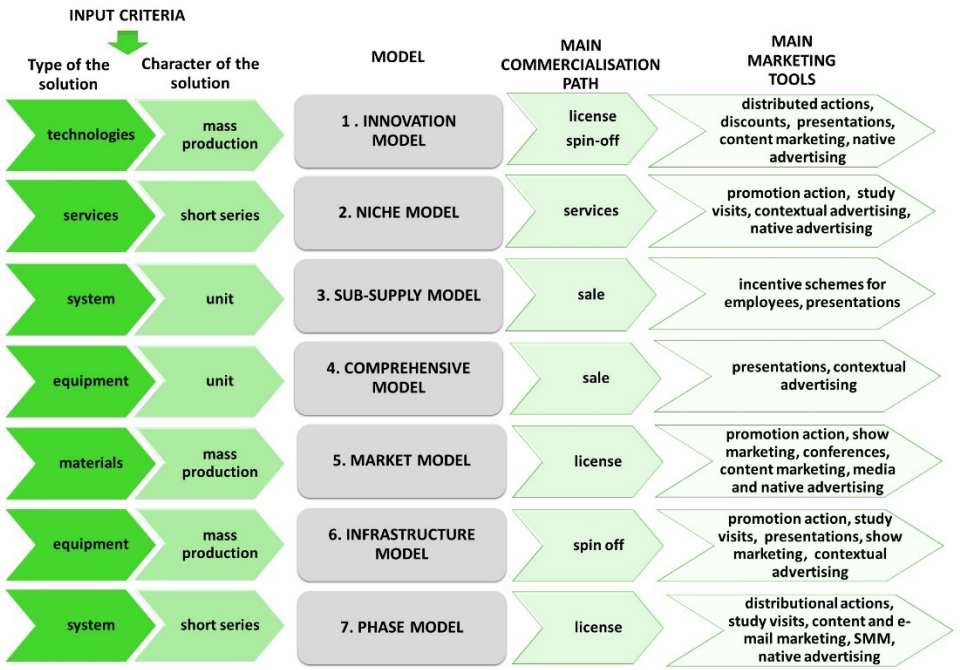

Fig. 1. Commercialisation models for an R&D organisation

tions should be converted into a specific utility for customers and have unique performance characteristics that are absent from products currently available on the market.

M2 — Niche Model is recommended when the results of the ongoing R&D work constitute new ways of conducting processes and solving important problems. It is dedicated to small-scale repeatable services that can be performed within a few days. Entrepreneurs use such services provided by R&D organisations because to perform them by themselves, they would have to engage knowledge and capital that is incomparably greater than the cost of services.

M3 — Sub-supply Model focuses on adapting the offer to the unique needs of the customer. The model is recommended for complex products that require close cooperation with buyers.

M4 — Comprehensive Model is meant for complex products, processes, or technologies. It is dedicated to solutions consisting of many interrelated elements, accompanied by various additional services that are offered both at the time of the purchase and later at the stage of operation.

M5 — Market Model is used when the results of the R&D work aim to solve social, civilisational, and environmental problems. The communication to potential customers should highlight how a solution can contribute to solving the above-mentioned types of problems that are currently relevant to society.

M6 — Infrastructure Model is based on the design and delivery of a complete technology along with new technological capabilities that enable new ventures to be started to provide mass access for potential customers.

M7 — Phase Model is designed for solutions that, after their testing in the laboratory and the semi-production phase, have a chance to be implemented in mass production by launching a new area of activity for an existing company, ensuring that it expands its product portfolio.

Regardless of the type of the commercialisation submodel, based on the literature review and the authors' experience in practical, industrial implementation of R&D results, while concurrently considering the specific conditions under which R&D organisations operate, the following stages of the commercialisation process at an R&D organisation are proposed:

I. generating an idea and developing an R&D solution corresponding to the market demand;

II. applying appropriate suitable implementation submodel (7MWwBP), depending on the result of the R&D work;

III. selecting and implementing marketing activities, depending on the principles of competition applicable to a given market, and including target segments; and

IV. carrying out horizontal activities strengthening the market position of the R&D organisation as an entity developing new products.

The effect of carrying out the commercialisation process based on the indicated points is to implement innovations developed by R&D organisations into economic practice.

For each submodel, a commercialisation path is proposed. Commercialisation may be direct or indirect (Lasambouw et al., 2021; Roszkowska-Mądra & Siemieniuk, 2020). The most common and basic paths of direct commercialisation are the sale of R&D results (direct sale — offering R&D results to economic entities, indirect sale — through intermediaries, e.g., wholesalers), granting a licence to use R&D results, and providing services with the use of R&D results.

Within indirect commercialisation, a spin-off company is set up. It consists in bringing R&D results to a commercialisation company, which is the most difficult commercialisation path, but it can potentially bring the greatest financial benefits.

There is no single best path for commercialisation. Each of them has its advantages and disadvantages, and the choice always depends on the specificity of the technology and its environment and the policy of the R&D organisation. For each submodel, the authors propose the most appropriate commercialisation paths (Table 3).

It should be noted that the current R&D market puts R&D organisations, including research institutes, in the position of companies offering services,

Tab. 3. Commercialisation paths proposed for individual 7MWwBP submodels

Submodel	Sale	License	Service	Spin off
M1	**	****	*	****
M2	***	**	****	*
M3	****	***	*	**
M4	****	***	**	*
M5	***	****	*	**
M6	**	*	***	****
M7	*	****	***	**

and it consistently enforces marketing behaviour in them. Unfortunately, R&D organisations lack marketing skills.

The successful commercialisation of innovations depends on effective marketing strategies (Kharchuk et al., 2014). The use of dedicated marketing tools, which help disseminate the information about R&D results in a non-random and customised manner, contributes to building a science–business relationship and acquiring business partners, which directly results in a more successful science-business knowledge transfer.

Thus, apart from the commercialisation path proposed for each 7MWwBP submodel, in order to allow practical application of the models in the innovation diffusion process, adequate sets of marketing tools are selected for each of them, first, to streamline the process of dissemination of research results obtained at R&D organisations, and then to facilitate commercialisation of these results. In the process of designing these sets of tools, a concept was applied for dividing marketing instruments into ALT (above the line) and BTL (below the line) groups, presented in contemporary publications (Tarasova et al., 2020). Considering the character of technological innovations developed and implemented by R&D organisations, the authors propose, with regard to this group of technological solutions, to apply the BTL activities that are targeted at the deliberately selected audiences. The main advantages of the BTL activities comprise the ability to reach a specific audience, effective and personalised communication, and the measurability of the effects.

For each of the seven submodels, a set of dedicated BTL marketing tools is proposed based on the experience of authors and other scholars in conducting commercialisation processes. BTL tools are divided into three areas (Tarasova et al., 2020) (Table 4):

- sales promotion (Tools 1–4);
- public relations (Tools 5–8); and
- internet advertising (Tools 9–14).

The proposed BTL tools are dedicated to the commercialisation paths indicated in Fig. 1. If the market implementation is successful, it is reasonable to modify the set of the marketing tools used. Furthermore, considering the feedback obtained from the market, it is possible to ensure a more effective commercialisation process by correcting the scope of the marketing activities carried out.

Tab. 4. BTL tools dedicated for 7MWwBP submodels

No.	BTL tools	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
1.	Promotion action with image-based communication	+	+++	++	++	+++	+++	+
2.	Distributional actions (direct sale)	+++	+	+	++	+	+	+++
3.	Actions focused on the growth of purchases (e.g., discounts for exceeding the volume of purchases)	+++	+	+	+	+	+	++
4.	Incentive schemes for employees	++	++	+++	+	++	++	++
5.	Study visits	++	+++	++	+	+	+++	+++
6.	Presentations – direct meetings	+++	++	+++	+++	+	+++	++
7.	Show marketing (events)	+	+	++	+	+++	+++	+
8.	Conferences	++	+	+	+	+++	+	++
9.	Content marketing (e.g., blogs)	+++	++	++	+	+++	++	+++
10.	E-mail marketing	+	++	+	++	++	+	+++
11.	SMM (social media marketing)	+	+	++	++	+	++	+++
12.	Contextual advertising	++	+++	+	+++	+	+++	+
13.	Media advertising	+	+	+	+	+++	+	++
14.	Native advertising	+++	+++	++	++	+++	+	+++

Legend : +++ recommended tools, ++ advisable tools, + tools of minor importance

Source: Elaborated by the authors (Poteralska & Walasik, 2021).

4. Good practice

The proposed submodels are used to support commercialisation processes at R&D organisations and increase their effectiveness by applying a structured approach and proposing specific steps, depending on the type and character of a technological solution. Moreover, the application of the submodels better focuses R&D organisations on the market, which is of key importance as the insufficient market-oriented approach and insufficient management, marketing, and commercialisation skills, mostly on the technology provider's part, are stressed as one of the important technology transfer barriers (Derakhshani, 1983; Harder & Benke, 2005; Mazurkiewicz & Poteralska, 2019). Strengthening the marketing orientation in an R&D organisation also facilitates its recognition as an organisation oriented towards the commercialisation of R&D results. The application of the models may also act as a boost for an R&D organisation's revenue from the sale or licensing of technologies, provision of services, or practical, industrial implementation of products with high commercial potential.

The models are applied in practice in the processes of technological innovation development and commercialisation at the Łukasiewicz Research Network – Institute for Sustainable Technologies. An example of an effective technology transfer, considering the proposed stages of the commercialisation process for R&D organisations, is the optical inspection system on production lines, which aims to increase the production efficiency and quality of products. The creation of this innovation in the form of know-how (design methodology) was a result of R&D activity (technology push); however, a reverse situation was also observed, namely, the shaping of R&D activities in the directions for which there is demand from companies (market pull) (Stage I of the commercialisation process). For the R&D result, based on the input criteria (type and character of the innovation), one out of seven submodels was suggested, i.e., the Sub-supply Model. This submodel is used when the offer is adapted to the unique needs of the recipient (Stage II of the commercialisation process).

Innovations dedicated to the metal and automotive industry, thanks to dissemination among similar companies, found more customers. Market segmentation, on the other hand, identified new industries in which the innovation was applied, among others in the tobacco industry (Stage III of the commercialisation process).

Undertaken image activities aimed to create a brand of an R&D organisation, showing successful implementations of R&D results, direct marketing, and presentations of success stories resulted in the start of cooperation with new entities and encouraged to implement the system on their production lines, in this case representing the food industry. An important element of Stage IV of the commercialisation process was to inform the existing and potential partners and business entities about the activities conducted in the area of creating a generation of new systems that are constantly being developed and whose operating ranges are continuously extended with new functionalities, e.g., the use of real-time systems, deep learning methods, or new sensors and illuminators from the entire optical radiation range, which resulted in the development of vision systems designed for the glass industry in accordance with the "zero waste" philosophy.

Conclusions

Increasing market pressure to develop innovations poses challenges to R&D organisations and other actors interested in technology transfer, consisting not only of focusing on innovation creation but, above all, on a comprehensive approach to the commercialisation process. In the case of a new technology or R&D results, several important decisions should be taken, including how to protect intellectual property, how to finance various stages of the innovation development process, or, finally, how to introduce new technology to the market, which the proposed models are intended to support.

The use of the proposed set of seven 7MWwBP submodels allows for individual treatment of each research result and product developed by an R&D organisation for the purpose of its commercialisation. The proposed submodels are general and flexible at the same time. They should not be treated as rigid, absolute procedural guidelines but as a proposal that facilitates the introduction of marketing orientation in an R&D organisation, affecting activities aimed at the commercialisation of R&D results. In comparison to the models described in the literature, it comprehensively considers the relationship between the models and the type and character of a technological solution, commercialisation path and a set of the marketing tools proposed for the effective commer-

cialisation of R&D results. The possibility to apply this customised approach to all types of R&D results developed at R&D organisations is, in the authors' opinion, the most important strength of the proposed model. The application of the model can be beneficial for researchers not only at the stage of planning and undertaking the commercialisation of an existing technological solution, but it also can be used at the stage of designing a new one while considering the potential future commercialisation path as early as at the stage of the idea generation.

As previously mentioned, a comprehensive approach is needed, and such is proposed within the model. However, there are still some aspects that are not covered. One of the most important limitations is the lack of market analyses incorporated with the proposed model. They are of key importance for effective commercialisation, and at present, they must be carried out independently of the model.

Another limitation comprises a lack of additional input criteria enabling a more detailed approach to R&D results concerning different aspects of the readiness level. Thus, the proposed future areas of the model development comprise, among others, the inclusion of additional input criteria. Such criteria have already been indicated as a result of the state-of-the-art analysis, and they comprise input criteria relating to Technology Readiness Level – TRL (Budi, Aldianto, 2020; Jou & Yuan, 2016), other (apart from TRL) indicators used for market-related technology assessment: Technology Needs Value (TNV), Integration Readiness Level (IRL), Innovation Readiness Diagram (IRD) (Budi & Aldianto, 2020), and the roles played by researchers in the framework of the undertaken entrepreneurial activities (Qian et al., 2018).

The authors wish to continue the development of the models. The set of marketing tools will be modified if the market conditions or the character of an R&D result change. Selected marketing tools should be more correlated with market segmentation. The need for a closer interrelation arises because a successful segmentation process is one of the key elements impacting the effectiveness of the process of commercialisation of R&D results. Market segmentation refers to the classification of potential customers of innovative solutions according to their needs and requirements. Therefore, market segmentation helps an R&D organisation identify the direction in which it should develop. Its segment-oriented marketing activities help to develop a technology in a specific and thoughtful direction. These aspects of market segmentation are planned to be strengthened during the future stages of the model development.

Another element related to market segmentation, which the authors believe may be crucial for the proper conduct of the commercialisation process, is the identification of industrial sectors that are vulnerable to technological changes and, thus, are also more eager to introduce innovations. The identification of these sectors may result in a need to verify the models already applied in practice, and it may be a factor contributing to changes in the proposed or planned commercialisation paths, depending on the specific characteristics of the sectors selected in the course of the market segmentation process.

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Turnover-mitigating effect of servant leadership on job performance

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ABSTRACT

Job performance is an extremely complex factor affecting organisational performance. The literature recognises factors impacting job performance positively and negatively. This article aims to verify the turnover-mitigating effect on the relationship between servant leadership and job performance. The developed moderated mediation model is empirically verified based on the data collected from 263 managers working in Poland's for-profit organisations. The results were analysed using Macro for IBM SPSS Statistics. It has been shown that employee turnover is a mediator in the job performance model based on turnover-mitigating servant leadership. Additionally, the influence of employees' dynamic capabilities has been analysed. The study revealed the significance of servant leadership in influencing job performance and the disruptive relationship between employee turnover and the impact of employees' dynamic capabilities in reducing employee turnover. This research provides practical implications for managers and organisations regarding selecting the right leadership style to improve employee job performance.

KEY WORDS

servant leadership, employee job performance, employee turnover, employees' dynamic capabilities, organisational performance

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Introduction

The contemporary literature provides numerous job performance models in the management science field (Schmitt & Chen, 1998; Campbell et al., 1993; Borman & Motowidlo, 1993). Many researchers attempt to determine factors having a significant impact on employee job performance, including the quality and timeliness of their work and the achievement of their goals (Rich et al., 2010). Undoubtedly, managers are one of the main factors that influence

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employee work in an organisation (de Waal & Sivro, 2012; Choudhary et al., 2013; Liden et al., 2015; Alafeshat & Aboud, 2019). Their skills, behaviours and attitudes affect employee performance (Liden et al., 2015; Schwarz et al., 2016; Mcquade et al., 2020; Awan et al., 2012). Since the last decade, leadership studies have started strongly emphasising the interaction between leaders and followers (Avolio et al., 2009). Analysing the influence of a supervisor on an employee, different leadership types must be considered, so the leadership impact on job performance may be different (Widelska et al., 2018). The literature distinguishes many leadership types, including human relations leadership, democratic leadership, laissez-faire leadership, and autocratic leadership (Warrick 1981). Other popular leadership styles are transformational leadership and transactional leadership (Bass, 1985; Politis, 2001; Bhatti & Alyahya, 2021). Recently, servant leadership has been recognised as an important leadership form (Mcquade et al., 2020).

Hence, this article refers to the impact of servant leadership on employee job performance. Servant leadership is a people-oriented leadership approach (van Dierendonck, 2011) focusing on serving others to enhance their development. It is argued that servant leaders combine motivation to lead with a need to serve others. A positive effect of servant leadership on job performance in the context of the literature on the subject (Liden et al., 2015; Schwarz et al., 2016; Mcquade et al., 2020; Awan et al., 2012) seems obvious. The servant leadership approach improves employee work motivation and engagement (Krog & Govender, 2015), resulting in increased work results. It seems, however, that apart from the obvious job-related constructs, such as work motivation, job satisfaction or work engagement (Price & Mueller, 1975; Allen & Meyer, 1990; Li et al., 2013; Bonds, 2017; Shelly et al., 2011; Sajjad et al., 2013), servant leadership also influences the employee intentions to leave the organisation. It seems that employees who develop and utilise autonomy and feel more responsible for their work would not be interested in leaving. Even more so, the lack of intention to leave the organisation would probably have a greater effect on their job performance. Therefore, by reducing an employee's intention to leave indirectly (more than directly), servant leadership will affect employee job performance. Therefore, this study aims to prove the impact of this mediation and develop a job performance model based on turnover-mitigating servant leadership. This aim fits into the research gap as the impact of servant leadership on employee performance through other factors has only been analysed to a very small extent (de Waal & Sivro, 2012), or analyses were performed in other research contexts (Krog & Govender, 2015; McCann et al., 2014).

Additionally, the article recognises the role of employees' dynamic capabilities in the analysed process of servant leadership impacting job performance. Different traits and features characterise employees. By analogy to the concept of dynamic capabilities by Teece (2009), it seems that nowadays, the employee potential expressed in their competences, i.e., knowledge, skills and characteristics, is becoming less important (Boyatzis, 1982) without the ability to use it depending on dynamically changing job needs. Employees' dynamic capabilities (EDC) is a concept developed by Bieńkowska & Tworek (2020). EDC can influence job performance through work motivation, job satisfaction, work engagement and, most importantly, PJ-fit. Hence, it seems that it may have the ability to mitigate the negative influence of employee turnover on job performance. Therefore, the study additionally aims to analyse the EDC influence on the relationship between servant leadership and job performance through employee turnover.

The expressed study aims are achieved by a systematic literature review concerning the analysed relations — presented in the first part of the article — and verified based on empirical studies presented in the second part of the article.

1. Theoretical background and hypotheses development

1.1. Job performance as a crucial factor for organisation

The high complexity of employee job performance explains its numerous definitions in the human resource management literature (Darvishmotevali & Ali, 2020). Campbell et al. (1993) argued that perceptions of employee job performance are determined by their point of view, which may lean towards understanding employee job performance as outcomes or as behaviours. If an employee's job performance is considered in the context of outcomes, it is essential to remember that job performance can also be considered two-dimensionally: as about efficiency and as about productivity (Pritchard, 1992). The core of the difference between efficiency and productivity is that efficiency refers to the degree of

effectiveness in producing the desired result, while productivity is explained as the effectiveness of productive effort, measured by the rate of output per unit of input (Darvishmotevali & Ali, 2020; Sujowa et al., 2019).

However, the perception of employee job performance in the context of outcomes is seemingly expected to remain mostly related to the behavioural aspect, as job performance perceived by outcomes assesses the results of employee behaviour in the organisation (Darvishmotevali & Ali, 2020). Therefore, employee job performance in the human resource management literature is most often defined in terms of behaviours expected by a company from an employee (Campbell & Wiernik, 2015; Motowidlo & Kell, 2012).

According to the theory by Motowidlo and Kell (2012), job performance is the total expected value to the organisation represented by a set of certain behaviours that an individual performs over time. Thus, the core of this definition is to determine the set of employee behaviours determining a high level of job performance (Podsakoff & MacKenzie, 1997; Smith, Organ, & Near, 1983). Researchers indicate that job performance is shaped by the general and organisation-specific knowledge, skills, and characteristics of employees (Campbell et al., 1993).

These observable individual behaviours demonstrated by employees affect the generated organisation's value and pursued goals (Cambell & Wiernik, 2015). The impact made by job performance on an organisation highlights the significance of this factor to organisational performance. Hence, the need exists for researchers to verify the job performance phenomenon and recognise the components that shape it.

1.2. Role of servant leadership in shaping job performance

Servant leadership was formally conceptualised by Robert Greenleaf, who stated that "the servant-leader is servant first [...] It begins with the natural feeling that one wants to serve, to serve first, then conscious choice brings one to aspire to lead" (Greenleaf, 1998, p. 4). Since then, there has been continuous advancement of research on servant leadership. Researchers examined definitions of servant leadership, its context, servant leader skills and behaviours, and scales to measure the concept (van Dierendonck, 2011; Parris & Peachey, 2013; Eva et al., 2019; Mcquade et al., 2020).

Most literature reviews servant leader's behaviour, characteristics, and skills (Mcquade, Harrison & Tarbert, 2020).

Many authors argue that servant leadership behaviour is demonstrated by empowering people (Spears, 1996), expressing stewardship (Spears, 1996; Russell & Stone, 2002; Brown et al., 2005), humility, and authenticity (van Dierendonck, 2011), inspiring, influencing (Sendjaya et al., 2008) and providing a direction to followers (van Dierendonck, 2011), and giving spiritual support (Avolio et al., 2009).

Empowerment aims to foster a proactive attitude among followers (van Dierendonck, 2011) and give them autonomy to make decisions about daily tasks (Krog & Govender, 2015). Employees perceive empowerment as a sign of trust from leaders, encouraging them to follow voluntarily and willingly. The notion of stewardship is derived from the stewardship theory (Davis et al., 2018). Leaders demonstrate a commitment to serving others' needs (Spears, 1996); however, their behaviour does not depart from the interest of their organisations. They behave pro-organisationally; hence, they are aligned with the objectives of their organisation (Davis et al., 2018). Servant leaders express humility admitting a possible benefit from the contribution and expertise of others (van Dierendonck, 2011). Humility is near modesty, demonstrated by retreating into the background and putting the interest of others first. Authenticity assumes expressing oneself truly, consistent with inner thoughts and feelings (Russell & Stone, 2002). Leaders demonstrate authenticity by doing what they promised and being honest.

Leaders also influence and inspire employees to approach situations from different angles and perspectives. They create a learning climate, where making mistakes is a practice to create self-awareness and develop self-efficiency. Provided directions allow employees to know what is expected from them. Leaders can provide the best direction towards planned goals by noticing followers' abilities and listening to their needs.

A leader's spiritual support aims to create a workplace that emphasises strong organisational values and a sense of meaning at work (Badrinarayan, 2008). Leaders have an important role in nurturing a spiritual workplace. They relate to employees' thoughts and beliefs to fulfil their spiritual needs at work. Spirituality and human-potential development are linked as leaders who create a spiritual workplace can reach the full potential of followers (Neck & Milliman, 1994).

The most important characteristic of servant leadership is the commitment to employee development manifested as an interest in the personal and professional life of followers (Spears, 1996). It is only possible if a leader possesses desired skills. Researchers state that a servant leader should possess empathy, have the ability to trust and be fair, and demonstrate communication skills (Spears, 1996; Avolio et al., 2009).

Servant leaders are considered empathic when they always accept and understand others. To perform, people need to feel accepted with all their features. Hence, empathy is an especially desired skill for leaders (Spears, 2010). Trust enables a leader to motivate followers to accomplish their goals (Krog & Govender, 2015). Employees trust leaders when they feel empowered. Fairness indicates leaders' sensitivity to the needs of others. Some researchers argue that leadership effectiveness depends on communication skills (Bass, 2000). The ability to articulate appropriately is essential for convincing and inspiring followers. However, listening is the most critical communication skill, manifested by automatically responding to any problem by intentionally listening to what has been said and unsaid. Servant leaders listen to understand followers' aspirations and to mentor them to achieve their goals (Schwarz et al., 2016)

Other attributes of a servant leader are honesty (Russell & Stone, 2002), integrity (Page & Wong, 2000), credibility, modelling (Schwarz et al., 2016), and creating a vision (Greenleaf, 1977). These features are observed in a specific leader's behaviour. There are still debates whether these are, in fact, skills or traits (Mcquade et al., 2020); however, both play an essential role in shaping servant leader behaviour. The current study proposes four key attributes: focusing on follower needs, stimulating, influencing, and developing others.

Servant leadership focuses on building a genuine, trust-based relationship with employees (Dutta & Khatri, 2017). This type of leadership, planting positive behaviours in the employees, encourages positive change, strengthening the employees' position in the organisation and, as a result, better fitting them to that organisation (Wong & Davey, 2007). Such leaders inspire employees to solve problems in various ways, create a learning space for employees, and give them a direction towards achieving goals by giving appropriate guidance (Greenleaf, 1997). A positive atmosphere allows employees to achieve work-related and mental goals (Kashyap & Rangnekar, 2016).

Many authors examine the relationship between servant leadership and other factors. Relationships have been found between servant leadership and employee empowerment, commitment, trust, and innovative behaviour (Krog & Govender, 2015), employee satisfaction (McCann, Graves, & Cox, 2014), organisational culture, organisational citizenship behaviour, and customer satisfaction (Setyaningrum, 2017), and organisational performance (de Waal & Sivro, 2012; Choudhary et al., 2013; Liden et al., 2015; Alafeshat & Aboud, 2019). One of the most significant relationships is with job performance (Liden et al., 2015; Schwarz et al., 2016; Mcquade et al., 2020; Awan et al., 2012).

Employee job performance is an extremely important factor that determines the performance of the whole organisation (Ugurluoglu et al., 2018). An organisation needs highly skilled, job-performing employees to achieve its goals, deliver quality products and services, and build its competitive advantage (Sriviboon, 2020).

The literature provides many interpretations of this factor. Schmitt and Chan (1998) classify job performance as "I can do", which refers to the knowledge and skills necessary to complete certain tasks, and as "I want to do", which is the level of an employee's motivation to work. For Campbell et al. (1993), performance theory was synonymous with observable behaviour. The effect of work has been understood as a direct result until June and Mahmood (2011) considered that the effects of work could also be determined by behaviour. Thus, the most relevant job-performance definition seems to be by Borman and Motowidlo (1993) as a set of behaviours that helps employees to perform their tasks and provide long-term work. Ensuring employee job performance is the most important task for managers, as people are considered one of the most important assets of an organisation (Ugurluoglu et al., 2018).

Liden et al. (2015) indicated three theoretical backgrounds explaining how servant leadership related to work outcomes at an individual level. First, servant leaders empower followers, fulfil their needs, and bring out their potential to enhance job performance. Leaders provide developmental support and autonomy creating the followers' self-efficacy. Empowerment and self-efficacy are positively related to job performance. Second, followers engage in work behaviours and perform required job duties well as a response to their leaders prioritising the followers' needs above their interest. Third, servant leaders act as role models by engaging in helping behaviours at

work and outside the company. Leaders have a strong sense of ethics, hence, employees trust and admire them, which ensures involvement in helping behaviours. Also, Schwarz et al. (2016) concluded that servant leadership was linked to job performance through role modelling emerging from the social learning process (Schwarz et al., 2016). Leaders shape employee job performance through their perceptions and attitudes. Servant leaders, being honest and trustworthy, also mobilise followers to become leaders themselves, hence, leading them towards higher work performance.

In the current study, job performance indicates employee productivity and is measured by work quality, timeliness, work efficiency and effectiveness in achieving goals.

Therefore, considering the above, the following hypothesis may be formulated: H1a. Servant leadership and job performance are related. The regularly changing trend in human resource management (HRM), increasingly focusing on the significance of employees in an organisation (Volosin & Volosinova, 2016), shows managers that people and their capital are becoming key to the success of the organisation (Sriviboon, 2020). Therefore, managers should focus on retaining the best employees in the organisation for as long as possible as the job performance of long-term staff can be beneficial (Armstrong, 2001). Therefore, HRM researchers increasingly focus on employee turnover (Hom et al., 2017).

This aspect has already been considered before, as many concepts and models describing the phenomenon of employee turnover have been developed so far (e.g., Mobley, 1977; Price & Mueller, 1975; Steers & Mowday, 1981; Allen & Griffeth, 2004). In the literature, the phenomenon of employee turnover can be presented in two ways: as a real factor for leaving employees and as an intention to leave. This conception has already been presented by Porter and Steers (1973). An employee's departure is defined as a process, while the intention to leave is a step in this process, determined by affective factors causing employee dissatisfaction (Aburumman et al., 2010). Unfortunately, the conducted research on employee turnover shows that it is impossible to clearly determine which factors or their group cause an employee's decision to leave the organisation (Bernthal & Wellins, 2001; Bellini et al., 2019). It seems reasonable to investigate employee turnover causes in specific groups of influencing factors, i.e., individual, related to the job characteristics model (Loher et al., 1985; Lee & Wilbur 1985; Michaels & Spector, 1982), and organisational, directly related to the HRM strategy (Ernst Kossek & Ozeki, 1998). Also, a leadership style seems to be a key factor (Fuller et al., 1999; Lok & Crawford, 2004; Burners, 2006; Lo, 2015). Researchers often indicate leadership as a factor related to employee turnover (Mobley, 1979; Clark, 2001; Elci et al., 2012).

The role of leadership is crucial in building a relationship between an employee and a leader. Moreover, as employees understand the organisation through the leadership style, it also impacts the organisational identity (Martin, 2009). Employee perception of the organisational identity influences their willingness to stay (Edwards & Edwards, 2013). Undoubtedly, leaders have a significant impact on employee behaviours and attitudes, including their motivation to stay or leave the organisation (Palanski et al., 2014, Wang et al., 2016; Turgut, 2017; Suifan et al., 2020). Leader characters, behaviours, decision-making and implementation methods influence employee attitudes and behaviours (Shipton, Sanders, Atkinson & Frenkel, 2016; Turgut et al., 2017). A leadership style, characterised by behaviours of leaders, methods used to make and realise decisions, their communication skills, and approach to people directly impact employees (Stone et al., 2004; Smith et al., 2004; van Dierendonck et al., 2014; Kashyap & Rangnekar, 2016).

Many servant leadership aspects successfully impact employees. Studies show that servant leadership also increases trust in the leader (Sendjaya & Pekerti, 2010), but above all, it improves cooperation between the leader and the organisation (Joseph & Winston, 2005; Stone, Russell, & Patterson, 2004; Zhang et al., 2012), and enhances organisational loyalty (Kool & van Dierendonck, 2012). Therefore, it especially positively impacts commitment to the organisation and willingness to stay (Liden et al., 2008; Dutta & Khatri, 2017). A leader with a natural tendency to serve followers prioritises employee developmental capabilities, is sensitive and empathic, which effectively increases employee job satisfaction (Mayer et al., 2008; van Dierendonck & Nuijten, 2011) and influences their turnover (Parris & Peachey, 2013; Jaramillo et al., 2009; Turgut et al., 2007). Based on the above consideration, the following hypothesis can be formulated: H1b. Servant leadership and employee turnover are related.

As mentioned above, employee job performance is extremely important in keeping organisational performance (Sriviboon, 2020). Currently, employee knowledge and talent have become a key factor in the

struggle for organisations to remain competitive in the marketplace (Smith & Kelly, 1997; Jamal & Saif, 2011; Johari & Yahya, 2012). New employees hired in place of those who left the organisation require attention and time, which costs money and reduces the performance of other employees (Beer, 1981; Butali et al., 2013). According to Armstrong (2001), an employee with long experience generally achieves better performance than a newly recruited staff member. Price (2001) also confirmed that the increased employee turnover rate resulted in lower productivity of the organisation due to the loss of qualified and experienced employees. This is particularly important as it turns out that employees with the highest job performance decide to leave the organisation more often (Jackosfky, 1986). Such employees have a much greater choice of employment opportunities due to competition between organisations, facilitating turnover (Jackofsky, 1984). Work engagement is also important for building an appropriate level of job performance, but it becomes irrelevant with a high rate of employee turnover, also decreasing job performance (Hulin et al., 1999).

The increasing turnover rate is a negative phenomenon from the perspective of employees who decide to stay in the organisation. It may lower the morale of employees and their engagement in daily work, resulting in poorer job performance (Armstrong, 2009; Branham, 2007; Katcher & Snyder, 2007). This aspect is crucial for the organisation as leaving employees decrease organisational knowledge and impact staying employees. This negative relationship between the intention to leave and job performance has already been confirmed several times in the literature (Schwab, 1991; Lee & Whitford, 2008; Moynihan & Landuyt, 2008; Meier & Hicklin, 2008; Koszela, 2020; Koszela & Tworek, 2020). Based on the above consideration, the following hypothesis can be formulated: H1c. Employee turnover and job performance are related.

In the context of the relationships described above, it seems there is a need to comprehensively explain the mechanism of the impact of servant leadership on job performance while analysing the mediating role of employee turnover. A leader with the servant leadership style can strengthen employee job performance (Gašková, 2020). However, it seems that considering these relationships in their entirety, including employee turnover, can explain the phenomenon of job performance strengthened by servant leadership. It will allow verifying and more comprehensively explaining the mechanism behind the servant leadership's influence on job performance. Servant leadership supports employees by improving their competence, creating a positive working and learning environment, and building a trust-based long-term relationship (Krog & Govender, 2015; Sendjaya & Pekerti, 2010). Trust in a leader certainly leads to trust in the organisation; therefore, it is essential in building long-term relationships with employees and strengthening their willingness to stay in the organisation (Stone, Russell & Patterson, 2004; Joseph & Winston, 2005; Wong & Davey, 2007; Zhang et al., 2012; Kool & van Dierendonck, 2012). Employees with a high level of willingness to stay in the organisation show higher levels of job performance under servant leadership (Liden et al., 2015; Schwarz et al., 2016; Mcquade et al., 2020; Awan et al., 2012). The employees assuming they will remain, are more involved in the life of the organisation and their work, so their job performance is higher (Armstrong, 2001). It is not by chance that the literature offers opinions on long-term employees being more productive than new staff members due to a better knowledge of the

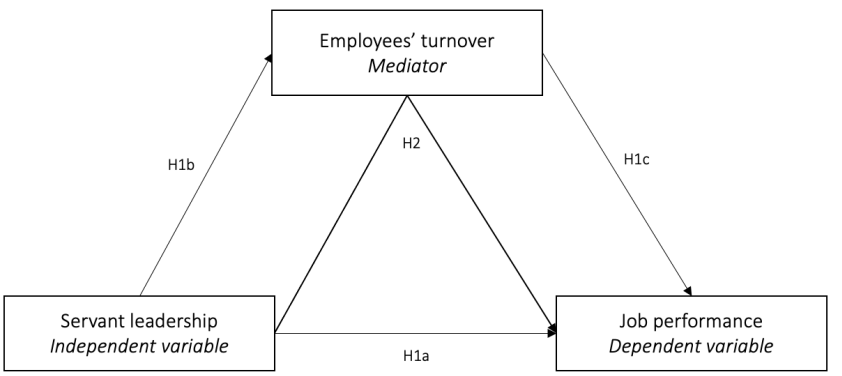

Fig. 1. Mediation model of the servant leadership's influence on job performance

business and internal processes of the organisation (Armstrong, 2001; Price, 2001; Beer, 1981; Butali et al., 2013). Therefore, in the light of the above, the main hypothesis should be formulated: H2. Servant leadership influences job performance (an indirect effect) through employee turnover (an intermediary variable).

1.3. Moderating role of EDC in shaping job performance by servant leadership

EDC means employees' dynamic capabilities, determining their ability to use competences (potential) flexibly or contribute with their potential in the context of changing needs and requirements. It is understood as "the capability to integrate, build and reconfigure employee competencies to address a rapidly changing environment that directly influences the performance of tasks in the workplace" (Bieńkowska & Tworek, 2020). EDC has the following components:

- "the ability to be sensitive to changes in the environment (the ability to see changes and recognise opportunities and risks potentially affecting the performance of work at the workplace),
- the ability to adapt to changes in the environment (the ability to undertake preventive actions, preventing the occurrence of problems in the workplace),
- the ability to proactively solve problems arising in the workplace (if they occur), and include innovations in the workplace,
- the ability for continuous personal development and learning" (Bieńkowska & Tworek, 2020).

Bieńkowska and Tworek (2020) proved that EDC positively influences job performance, and this influence takes place through intermediary variables, i.e., in order of P-J fit, and then on work motivation, job satisfaction, work engagement and organisational commitment (Bieńkowska & Tworek, 2020).

It seems that the EDC level may be a factor influencing the servant leadership impact model on job performance through employee turnover. It will be a moderator of the relationship between employee turnover and job performance and between servant leadership and employee turnover, which means that EDC may have the potential to strengthen the relationship between servant leadership and job performance.

It should be assumed that EDC influences both employee turnover and job performance. While the impact on job performance is proven (Bieńkowska & Tworek, 2020), the impact on employee turnover has not been analysed so far and remains unclear. On the one hand, EDC allows an employee to adapt to changes in the organisation and its environment (internal impact). On the other hand, an employee with high EDC is more willing to change their job because they have a greater potential for adaptation (assuming they have due to the specifics of the EDC components described earlier), and thus lower barriers to leaving the organisation. However, they are held back by "benefits" from EDC: such as PJ-fit, work motivation or job satisfaction. In this context, one should first consider the situation when an employee has low EDC.

Low EDC is indicative of employee inability to adapt to necessary changes in their job, which may become the reason to leave it and which may naturally lower job performance. Independently of the intention to leave, an employee with low EDC fails to achieve high job performance (because of the inability to meet job requirements). Consequently, they may consider leaving their current job because they lack the potential to adapt to new working conditions. However, the higher are EDC, the better is the

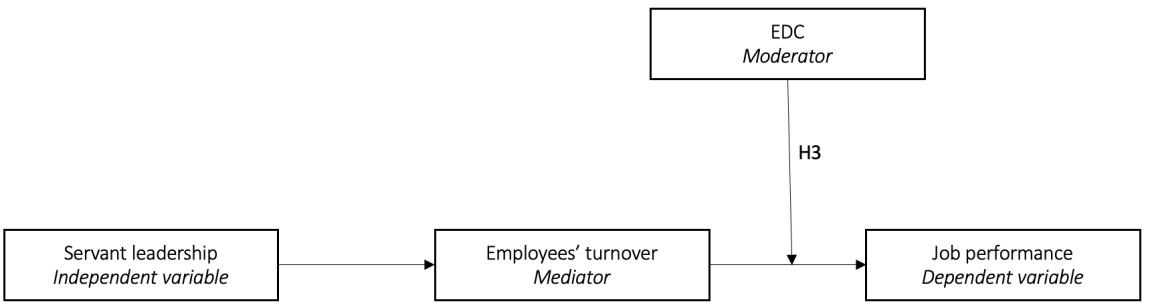

Fig. 2. Moderators of the model of servant leadership's influence on job performance

employee's ability to adapt to changing job requirements.

As a result, the employee's motivation and job satisfaction increase, the intention to leave is weakened, and the impact of employee turnover on job performance is stronger. In this context, the following hypothesis can be put forward: H3. The higher is the EDC, the stronger is the influence of employee turnover on job performance (in the mediation model).

The diagram illustrating the described research hypothesis is presented in Fig. 2.

2. Research methodology

The proposed hypotheses were verified based on an empirical study. The main research was conducted using a CAWI method in December 2019 in 263 organisations located in Poland, which was the only condition limiting the sample (organisations were surveyed regardless of their size, industry, the type of business etc.). The sample was obtained with the cooperation of an external company specialising in empirical research in social sciences, which ensured that questionnaires were filled by respondents in managerial positions with the view of the entire company.

It was preceded by the pilot survey conducted in the fourth quarter of 2019 in the group of 25 managers (acting as competent judges). According to obtained results, some ambiguous questions were rewritten. It was established that proposed questions were understood by respondents as intended by researchers (which is a prerequisite for establishing a questionnaire as a valid measurement method (Czakon, 2019)). The overview of the sample is shown in Table 1. It confirms that the sample is sufficiently diversified to form scientific conclusions based on the obtained results. The results were analysed using Macro (v.3.5) for IBM SPSS Statistics (v. 25).

2.1. Overview of variables

The hypotheses verification was based on four key variables: Servant Leadership, Employee Turnover, Job Performance and EDC. The variables were measured based on dedicated scales, including statements assessed using a 5-point Likert scale.

Servant Leadership was measured based on four items and reflected a relationship-based approach between a leader and a follower, a manager's focus on followers' needs, supporting them in development, inspiring, motivating, and influencing to achieve better performance. A 5-point Likert scale (from "I strongly disagree" to "I strongly agree" with a middle point "I have no opinion") was used as a basis.

Employee Turnover was measured based on the scale of the employee intention to leave the organisation. One item was used for measurement. A 5-point Likert scale (from "I strongly disagree" to "I strongly agree") was used as a basis.

Job Performance was measured based on four items covering work quality, timeliness, work efficiency and effectiveness in achieving goals. A 5-point Likert scale (from "I strongly disagree" to "I strongly agree") was used as a basis.

EDC was measured based on four items covering four components of EDC. A 5-point Likert scale (from "I strongly disagree" to "I strongly agree") was used as a basis.

Tab. 1. Research sample characteristics

Organisation size	Manufacturing organisations	Service organisations	Trade organisations	Total
Micro (below 10 people)	12	11	9	32
Small (11–50 people)	37	15	11	63
Medium (51–250 people)	42	26	24	92
Large (above 250 people)	37	11	28	76
Total	128	63	72	263

Source: Tworek & Koszela (2020).

3. Research results

3.1. Descriptive statistics and the reliability analysis of scales

The reliability of scales for each variable was verified as a first step of the presented research. The results are presented in Table 2. The obtained results show that Cronbach's α was high for every variable, which indicates a high internal reliability of the scales and measurements.

3.2. Mediation model

Three conditions must be met to establish the mediation model (Saks, 2006). First, there must be a relationship between the independent variables and the mediator. Second, there must be a relationship between the dependent variables and the mediator. Third, a significant relationship between the independent variables and dependent variables must be reduced (partial mediation) or no longer significant (full mediation) when introducing the mediator.

Therefore, to verify those conditions, the r-Pearson correlation analysis was performed (Table 3). It was also a basis for the verification of hypotheses H1a–H1c.

The obtained results, presented in Table 3, clearly show a statistically significant and high correlation between all analysed variables. The correlation is the highest in the case of the relationship between leadership and job performance. It allows the initial acceptance of H1a, H1b and H1c hypotheses.

Therefore, such a conclusion enables the next step: to verify the mediation model of job performance. To do that, linear regression analysis with the mediator was performed for servant leadership as an independent variable and job performance as a dependent variable. The inverted employee turno-

Tab. 2. Defined variables along with the results of the reliability analysis of scales

No.	Variable	No. scales	Cronbach's α	Factor analysis [%]	M	SD
1.	EDC	4	0.742	56.369	3.43	0.76
2.	Servant leadership	4	0.777	60.065	3.40	0.82
3.	Employee turnover	1	--	--	3.44	0.99
4.	Job performance	4	0.816	64.721	3.69	0.75

Tab. 3. Correlation analysis between analysed variables.

Variable		Employees' turnover	EDC	Job performance
Servant leadership	r	-0.225	0.645	0.556
	Sig.	<0.001	<0.001	<0.001
	N	255	255	255
EDC	r	0.086	1	0.623
	Sig.	0.165		<0.001
	N	263	263	263
Job performance	r	-0.403	0.623	1
	Sig.	<0.001	<0.001	
	N	263	263	263

ver was tested as the mediator in the model (employee turnover is assumed to have a negative mediating effect on the relationship between servant leadership and job performance; therefore, it was necessary to invert it to test the hypothesis). The results of the analysis are included in Table 4.

The obtained regression model with the mediator is statistically significant (F(2.252)=78.197 and corrected R2=0.618). Moreover, employee turnover is a statistically significant mediator of the model ($p<0.001$, coeff. = 0.210, se = 0.038). The mediating effect is also statistically significant, as can be observed in Table X (BootLLCI and ULCI are both above 0). The obtained model shows that employee turnover is a weak mediator of the relationship between servant leadership and job performance. Therefore, it allows accepting hypothesis H2.

3.3. Moderator analysis for the EDC — research results

The obtained mediation model (hypothesis H2) was analysed in the context of EDC to verify their statistical significance as moderators of the relationships given in the model. The hypotheses were tested using linear regression analysis with the moderator. To do so, a moderator was introduced as a new variable in the relationship. It was built as a product of two independent variables, which have been standardised.

The first one was a base one for comparison (and only independent variables were added as predictors). The second one used independent variables and the moderator as predictors. The aim was to verify the occurrence of the moderating influence in the entire sample. To confirm it, the third model was introduced using the moderator and one independent variable as predictors. The results of the analysis are presented in Table 5.

The obtained research results show a cause–effect relationship between Servant Leadership, Employee Turnover and Job Performance, which is another way to verify the proposed model (H2). Moreover, the obtained results clearly show that EDC is a statistically significant moderator only in the case of the second relationship between Employee Turnover and Job Performance (F(4.250)=61.598, $p<0.001$). Therefore, as shown in Table 5, obtained results are the basis for accepting hypothesis H3. The hypotheses can be accepted, stating that EDC is a moderator in a given mediation model.

4. Discussion of the results

The article mainly aimed to verify the job performance model based on turnover-mitigating servant leadership, determining the turnover-mitigating effect on the relationship between servant leadership and job performance. The research results proved that the formulated model was correct and should be developed further.

There is a direct relationship between servant leadership and employee turnover, where servant leadership supports the willingness of an employee to stay in the organisation. A servant leader creates positive conditions for employee development and ensures employee autonomy, contributing to

Tab. 4. Results of the regression analysis with the mediator

Mediator	Direct effect value	Indirect effect value	BootLLCI	BootULCI	R^2
Employee turnover	0.445	0.057	0.015	0.1155	0.618

Tab. 5. Regression models' statistics

Model description	R^2	Delta R^2	Moderator coeff.	Standard error	t Stat	P Value
Employee turnover, EDC, Moderator *dependent v.: job performance*	0.704	0.014	0.099	0.036	2.695	0.007

employee retention (Greenleaf, 1997; Kashyap & Rangnekar, 2016). As employees understand organisational identity through management style, the relationship with the leader affects organisational identity (Martin, 2009). There is also a relationship between servant leadership and job performance, which shows that a supporting leader can strengthen employee job performance. Furthermore, there is a direct relationship between employee turnover and job performance.

It means that if an employee is determined to leave the organisation, their job performance is lower, and if the intention to stay in the organisation is strong, their job performance is high. Identifying the negative relationship between employees' turnover and job performance is extremely important because finding the factors that reduce job performance will help to avoid this phenomenon and facilitate job performance, which is extremely important for the performance of the organisation as a whole (Sriviboon, 2020).

Thus, the relationship between servant leadership and job performance mediated by employee turnover has been proven. This means that servant leadership strengthens job performance as long as employee turnover is low. Once it increases, the leader's support for job performance weakens or ceases to be relevant.

Therefore, to reduce employee turnover, EDC was introduced into the mediation model as a relationship moderator which supports job performance, which has already been proven (Bieńkowska & Tworek, 2020), and impacts employee turnover. As EDC supports employee fit for the job, motivation for work, or satisfaction with the job, it contributes to increasing the willingness to stay in the organisation. An employee with high dynamic skills adapts more quickly to any changes taking place in the organisation, so in the face of changes (Bieńkowska & Tworek, 2020), the employee does not decide to leave the organisation.

An employee's satisfaction with working conditions also weakens the desire to leave the organisation. This research provides vital information for organisations dependent on the right leadership style to take care of employee job performance. Employee turnover, expressed as employee willingness to leave the organisation, is a risk to this relationship. EDC not only reduces employee turnover but also supports job performance as an employee with such skills adapts to the job better, which makes work more efficient.

Conclusions

The article focuses on an essential aspect related to shaping employee job performance in an organisation through servant leadership.

Employee job performance is a vital aspect for an organisation due to the significant impact on organisational performance; therefore, knowledge of any factors that positively shape job performance is crucial for organisational performance.

However, based on research, this relationship is not as simple as might be expected, as it can be affected by employee turnover on the one hand and supported by EDC on the other. Therefore, it has been shown that employee turnover is a mediator in the job performance model based on turnover-mitigating servant leadership, i.e., when it reaches a high level, it mitigates the servant leadership's influence on job performance.

Moreover, EDC is a moderator that limits such influence on employee turnover and causes servant leadership to strengthen job performance. The formulated conclusions seem to be important for organisations as they not only indicate the kind of risks associated with high employee turnover but, most importantly, how they can be eliminated.

Therefore, the study provides essential information for the organisational managers about the significance of servant leadership in influencing job performance, but also about the disruptive relationship between employee turnover and the impact of EDC on reducing employee turnover. It is, therefore, essential for managers to develop an effective strategy for selecting employees for the organisation, focusing on verifying the level of their EDC, which reduces the negative effects of employee turnover.

So far, there have been no verified models which consider the negative impact of employee turnover that could be mitigated by EDC. Thus, it can be concluded that the research gap has been partially filled, and the current considerations on job performance have been significantly improved. Unfortunately, this research topic has not been fully exhausted in the article. Nevertheless, the results of the research and the indicated tips can serve as inspiration for further exploration of the job performance model based on turnover-mitigating servant leadership. The verified model can be further developed by adding other job-related characteristics. It is, therefore, worth finding additional factors that positively influence employee retention in the organisation.

The research can be improved with more empirical data. The statistical methods verifying research results have some limitations related to the use of a limited group of organisations located in Poland only.

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Research themes on the quality of public services exemplified by healthcare services — a bibliometric analysis

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ABSTRACT
The growing competition for customers requires constant improvement of service quality, continuously raising the importance of this matter and the significance of the entire service sector. Essentially, service quality concerns not only the private but also the public sector. Service quality in the public sector has already been widely discussed in the literature. Among research themes in the frame of public service quality, the healthcare sector attracts particular attention from researchers. Therefore, this study aimed to identify research topics on the public service quality and healthcare quality discussed in the SCOPUS database from 2012 to 2022. A bibliometric technique and the VOSviewer software were used to analyse over 25 000 articles on public service and healthcare service published over ten years. As a result, a total of ten research themes were set up, five in the healthcare sector and five in the public sector, which were linked using keywords and presented on maps. The identified research themes demonstrate the most popular research directions and indicate research gaps related to the subject.

KEY WORDS
quality, public service, healthcare service, bibliometric analysis

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Introduction

Service quality and customer satisfaction are important and widely discussed topics in the modern world of service. At the same time, they remain the most popular topics examined in the literature (Khudhair et al., 2019). The idea is considered extremely abstract and complicated; thus, there is no universal definition of service quality (Abbasi-Moghaddam et al., 2019; Brady & Robertson, 2001). The right service management is known to increase the level of con-

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sumer satisfaction and turn random buyers into loyal clients. This leads to repurchase, the spread of positive reviews and less attention to manipulations of the company's contenders, having a direct positive impact on the company's lower expenses (Juhana et al., 2015) and steady high financial results (Kassim & Abdullah, 2010; Hapsari et al., 2017). At the same time, healthcare service is an essential element in every country (Javed & Nawaz, 2019). Like any other, the healthcare service covers various activities executed by different service providers, such as doctors, nurses and support staff. Having a great impact on the country's economy and the well-being of its inhabitants, the healthcare sector has recently received ample attention (Bahadori et al., 2018). Despite a significant amount of research concerning quality, prolonged studies related to service quality need to be conducted (Li, Ma & Qu, 2017). This paper aimed to identify research themes on public service quality and healthcare quality discussed in the SCOPUS database from 2012 to 2022.

Bibliometric analysis (BA) was selected as the technique for achieving the research aim. BA is based on quantitative literature analysis and helps to construct and visualise database networks (Broadus, 1987). This method uses advanced clustering techniques for presenting the frequency and co-occurrence of keywords related to scientific publications, citations, co-citations, or co-authoring analyses (Montero-Díaz et al., 2018; Siderska & Jadaan, 2018; Cichowicz & Rollnik-Sadowska, 2018; Dias, 2019; Szpilko et al., 2019). Not only the influence of a publication could be analysed but also the subject's expansiveness in the literature, also identifying the latest trends (Uribe-Toril et al., 2018).

1. Literature review

As it is difficult to fully grasp the nature of service quality, the literature presents various definitions. Parasuraman, Zeithaml, and Berry (1985) characterised service quality as the discrepancy between what consumers expect and what they percept. Meanwhile, Chien and Tsai (2000) regarded that service quality was based on a harmonious combination of both consumer expectations and perceptions. In both cases, consumer satisfaction is an integral part of service quality. It is suggested that consumer satisfaction amounts to consumer loyalty, which directly depends on the level of satisfaction with the service provided to clients (Khudhair et al., 2019; Al-Tit, 2015). However, lately, customer communication methods and practices have greatly changed due to online networking modifications (Kumar et al., 2009).

Consumer loyalty is described as a mix of societal and attitudinal measurements, which are rather hard to break down (Hu et al., 2009). It is usually strengthened by consumer satisfaction, which depends on the positive correlation between client desires and a company's presentation (Khudhair et al., 2019). According to Taylor and Baker, service quality and customer satisfaction are two elements crucial for the client's fidelity because they inspire client purchases (Oh & Kim, 2017).

The healthcare sector is continually growing and has become extremely competitive (Islam et al., 2016; Gadowska & Różycka, 2016; Trigo, 2016). The rivalry is also boosted by a variety of private and public healthcare organisations (Kalaja et al., 2016). Therefore, to be accepted and become competitive, a healthcare organisation is required to provide high-quality service.

Many researchers have conducted studies on the healthcare sector. The popularity of the topics can be explained by the importance of data for policymakers and the necessity to reduce health disparities (Muir et al., 2010). Client satisfaction also plays a significant role as satisfied patients are more likely to track their healthcare outcomes, adhere to their treatments and are less often admitted to hospitals (Bleich et al., 2009).

At the same time, the variety of used approaches makes it rather complicated to compare studies written on this subject. For example, while some surveys are based on the assessment of the idea of "service quality" in healthcare (Abbasi-Moghaddam et al., 2019; Ampah et al., 2019; Fatima et al., 2018; Fauziah et al., 2019), other studies concentrate on various elements of "service quality" (Chang et al., 2019; Gupta & Singh, 2017; Ibrahim & Ahmed, 2019; Jebraeily et al., 2018). Also, some authors focus on either patient satisfaction (Amankwah et al., 2019; Javed & Nawaz, 2019; Kwateng et al., 2017; Meesala & Paul, 2018; Mohammadi-Sardo & Salehi, 2019; Ng & Luk, 2018) or patient loyalty (Meesala & Paul, 2018) while ignoring other notions.

The same problem is observed with consumer satisfaction. It is also difficult to measure due to the lack of a unique definition and different approaches to measurement (Crow et al., 2002; Hudak & Wright, 2000; Sofaer & Firminger, 2005). While some researchers concentrate on how the type and quality of healthcare service influence patient satisfaction (Jackson et al., 2001; Nguyen et al., 2002), other scholars show the impact of healthcare service quality on

the health system generally (Blendon et al., 2003; European Commission, 2002). As a result, consumer satisfaction has started to be measured by focusing on some elements of patient experience, such as relations with healthcare providers, material values of healthcare organisations, waiting time, etc. (Sar et al., 2009; Chakraborty & Dobrzykowski, 2014). Also, the WHO proposed to add the healthcare system's "responsiveness" to this list, which is likely to pressure hospital providers to increase patient safety and decrease costs (Valentine et al., 2003). At the same time, it is highly important for the management of healthcare organisations and providers to focus on the constant improvement of the customer satisfaction level (Zendehtala et al., 2020) because of its positive effect on higher satisfaction of employees and patients, which directly leads to increased patient loyalty and encourages positive recommendations (Ramli, 2019; Oluma & Abadiga, 2019). All of this results in minimising costs, stabilising structure and increasing the efficiency of healthcare organisations (Shepperd et al., 2016, p. 2).

2. Research methodology

In an era of the increasing number of publications, identifying research themes and research gaps is challenging (Szum, 2021; Winkowska et al., 2019). This has led to a growing interest in quantitative methods of scientific publications' assessment, such as bibliometric analysis (BA). Earlier, BA was defined as a statistical literature analysis for describing qualitative and quantitative changes in an assumed scientific research theme (De Bakker et al., 2005). In the wide sense, bibliometrics means "infometrics" (Wolfram, 2003), whereas, in the narrow sense, it is referred to as "scientometrics" (Bar-Ilan, 2010). Nevertheless, the word "webometrics" precisely shows the nature of this technique as it is totally computerised and closely connected to the web.

Therefore, considering a significant number of papers, which have been published online, this technique is very popular for conducting a literature analysis. BA focuses on a plethora of aspects, including geographical and institutional (Lin, 2012; Zhuang et al., 2013), with some elements related to the performance of publications, like development over periods (Huffman et al., 2013), subject domains or disciplines (Liu et al., 2012; Zibareva et al., 2014). Besides, there are many subject areas where this technique can be applied, e.g., tourism and hospitality (Koc & Boz, 2014; Köseoglu et al., 2016; Park, 2019), environmental aspects (Zhang et al., 2019; Liu et al., 2019; Sarkodie & Strezov, 2019) and management (Kumar et al., 2019; Fernández & Berbegal-Mirabent, 2019).

Within the conducted bibliometric analysis, publications from the Scopus database for the last ten years (2012–2022) with keywords "service quality", "public service", and "healthcare service" were used to collect bibliographic data. As a result, two research theme maps were prepared.

The proposed methodology included three stages. First, the occurrence was established for keywords "quality" and "public service" for the first map

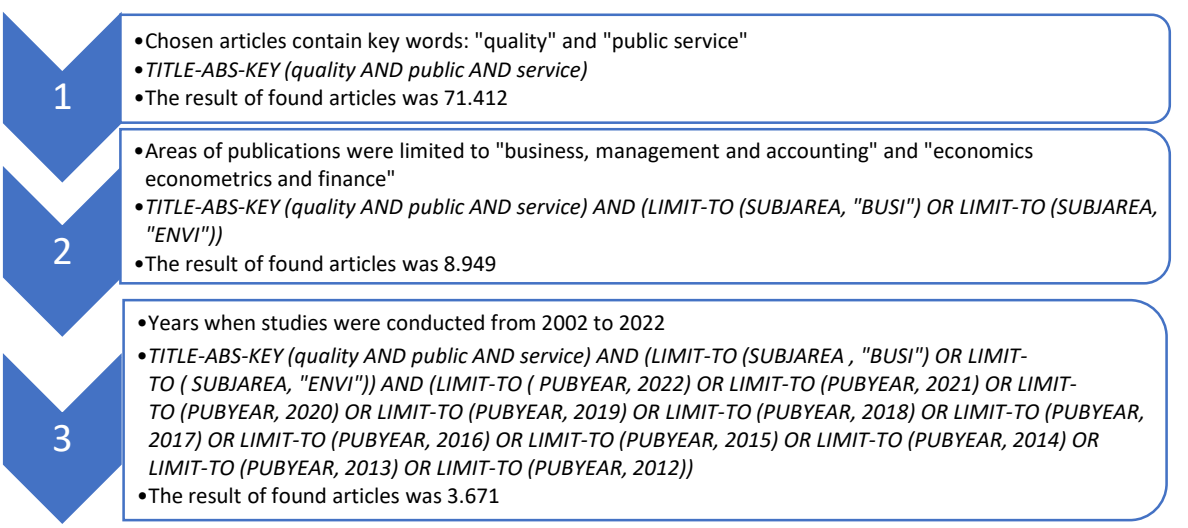

Fig. 1. Flowchart for gathering data on publications for the central theme and sub-themes in relation to public service

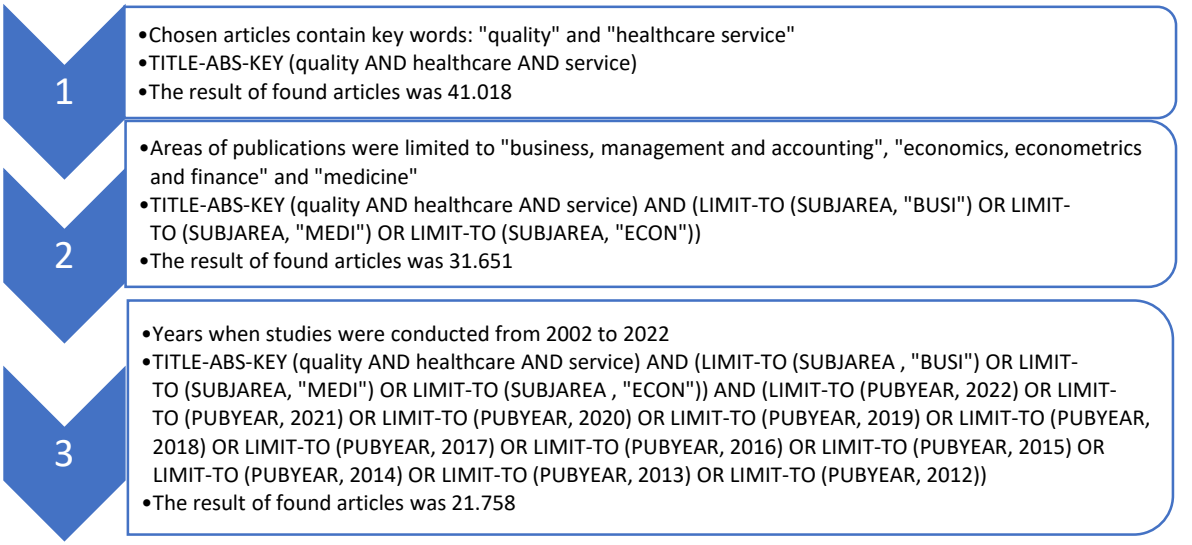

Fig. 2. Flowchart for gathering data on publications for the central theme and sub-themes in relation to healthcare service

Tab. 1. Ranking of the most productive countries

Public service quality			Healthcare service quality	
Rank	Country	Number of publications	Country	Number of publications
1	United States	580	United States	6782
2	United Kingdom	332	United Kingdom	4087
3	India	231	Australia	1830
4	Italy	191	Canada	1740
5	China	185	Germany	891
6	Indonesia	156	Netherlands	886
7	Spain	154	Italy	872
8	Australia	153	India	748
9	Russian Federation	153	Spain	690
10	Malaysia	141	China	684

Source: Elaborated by the author based on the VOSviewer software.

and "quality" and "healthcare service" for the second map. Then, the research area was limited to the fields "business, management and accounting" and "economics, econometrics and finance" for the first map. An additional field, "medicine", was used for the subject of healthcare service quality. Ultimately, both research areas were limited to the period from 2012 to 2022, resulting in 3671 articles for the public sector study and 21758 articles for the healthcare sector study. All research stages for the public and healthcare service research are presented in Figs. 1 and 2, respectively.

The data was processed using the VOSviewer software, which is useful for working out a sheer volume of data (Gudanowska, 2017). The program was used to identify existing relationships between keywords characterising the articles from the scientific databases. The visualisation is presented using clustering techniques and advanced layouts (Magruk & Rollnik-Sadowska, 2021), such as the higher frequency of elements, the bigger and darker the label in the analysed set. The frequency of the elements' co-occurrence can be judged based on their proximity: central elements correspond to a larger and more diverse group of elements, whereas elements on the edges of the map usually belong to isolated fields; otherwise, distant elements either do not appear together or do it very rarely. Besides, different colours stand for different clusters formed by the most common elements (Rollnik-Sadowska, 2019).

Table 1 illustrates the ranking of the most productive countries with the largest share of publications on public and healthcare service quality. Although the total number of studies on the healthcare service far outstripped the public sector, it is clear that the United States is the most popular country in both cases, with the output of 25 % and 35 % of publications on the public and healthcare service, respectively. The second place in both cases is occupied by UK authors who have published 15 % of articles with the keyword "public service" and 21 % of articles with the keyword "healthcare service". At the same time, 231 publications about the public service were announced by authors affiliated with India. Their share of articles makes up 10 % of the total amount and puts it in third place, whereas in healthcare service, the third place is taken by Australia with 1830 publications (9.5 %).

3. Research results

To create a map with the keywords "public service" and "quality" in the VOSviewer program, a minimum of five keyword occurrences were selected, and as a result, 275 items were determined. In the case of the keywords "healthcare service" and "quality", the occurrences of keywords were the same, but the number of selected words was 255. Five main clusters were identified in areas of public service quality and healthcare service quality, and five research themes were established on the basis of these clusters in both fields. The cluster keywords and identified themes are presented in Table 2.

Analysing the identified research themes in the areas of public service quality and healthcare service quality, which have already been developed and com-

Tab. 2. Research themes in the areas of public service quality and healthcare quality in the SCOPUS database in 2012–2022

Public service quality		
Cluster number	**The main keywords**	**Research theme**
1	Service quality, customer satisfaction, public service, accessibility, Internet, industrial, public administration, SERVQUAL, urban, social, hospitals	Customer satisfaction and methods of assessment
2	Budget, cost, economics, funding, public health, health care, quality of life, control	Influence of cost on service delivery and quality of life
3	Communication, hospital, administration, organisation and management	Organisational structure and culture
4	Adult, aged, demography, female, health, status, socioeconomics, factors, age, patient satisfaction	Demography and patient satisfaction
5	Child, poverty, politics, human experience, social behaviour, social welfare, financial, responsibility	The policy of inclusive access to public services
Healthcare service quality		
Cluster number	**The main keywords**	**Research theme**
1	Well-being, quality of life, body mass, chronic disease, diabetes, health behaviour, health programme, recourses, hospitals, patients, treatment, risks	People's well-being and quality of life with the support of health programmes
2	Communication, cooperative behaviour, attitude to health, education, expectation, human, patient, participation, safety, perception, satisfaction	Patient perception of the healthcare service
3	Female, demography, child, global health, health equity, reform, maternal health, pregnancy, public health, availability of care, residents of a rural area	Availability of care for vulnerable groups
4	Cancer, family, community, neoplasm, psychology, health needs, terminal care, health care needs and demand	Healthcare needs and demands in the life cycle
5	Adult, mental disorder, mental health service	Mental health service

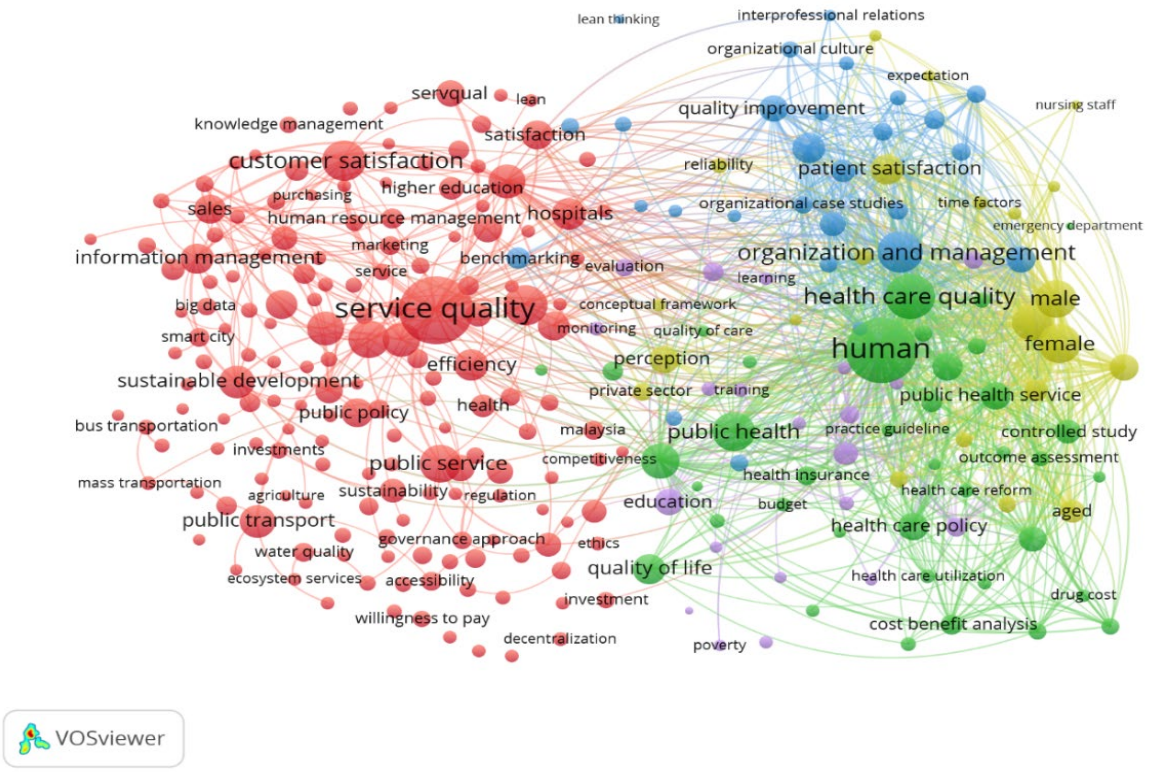

Fig. 3. Map of research themes based on the co-occurrence of keywords in publications referring to public service quality from the SCOPUS database

Source: Elaborated by the author based on the VOSviewer software.

mented on in the literature listed in Table 2, it is clear that in public service quality research themes, the links with health services occur in almost every cluster. This finding confirms the choice to extract the healthcare service quality as a separate field in the frame of public service.

Following the bibliometric analysis of the publications referring to public service quality (Fig. 3), it could be seen that the most extensive are two main elements associated with public service: "service quality" and "human".

The first cluster (Cluster 1), with the service quality at the centre, includes 166 keywords and connects closely with public relations, associated with marketing and customer satisfaction. Customer satisfaction was mainly inspected in relation to public transport, higher education and healthcare. SERVQUAL is the method used for the evaluation of quality in public services (including the healthcare sector) (Newman et al., 2001). Benchmarking is another method connected with the quality of public services and associated with the evaluation of marketing and management in human resources (Pesquita et al., 2009). Cluster 1 includes the accessibility and governance approaches to the public transport regulation. Besides, papers in this cluster deal with investments in the sustainable development of public relations and efficiency of service quality, which seems to be worth noting while aiming to deliver high-quality service.

The second cluster (Cluster 2) contains 38 keywords and mainly concentrates on humans as the main object in the assessment of public service quality. There is a clear relationship between healthcare quality and other elements of this cluster, such as healthcare policy, healthcare cost, economics and the quality of life, having a direct influence on the quality of the provided service. As a result, many studies and cost-effectiveness analyses have been conducted and, therefore, are illustrated in Cluster 2 to show the impact of healthcare service on the quality of life.

The third cluster (Cluster 3) contains 28 keywords and is mainly focused on how to organise and manage work to improve service quality. Evidently, the healthcare sector plays a significant role in this area. The map demonstrates that the healthcare ser-

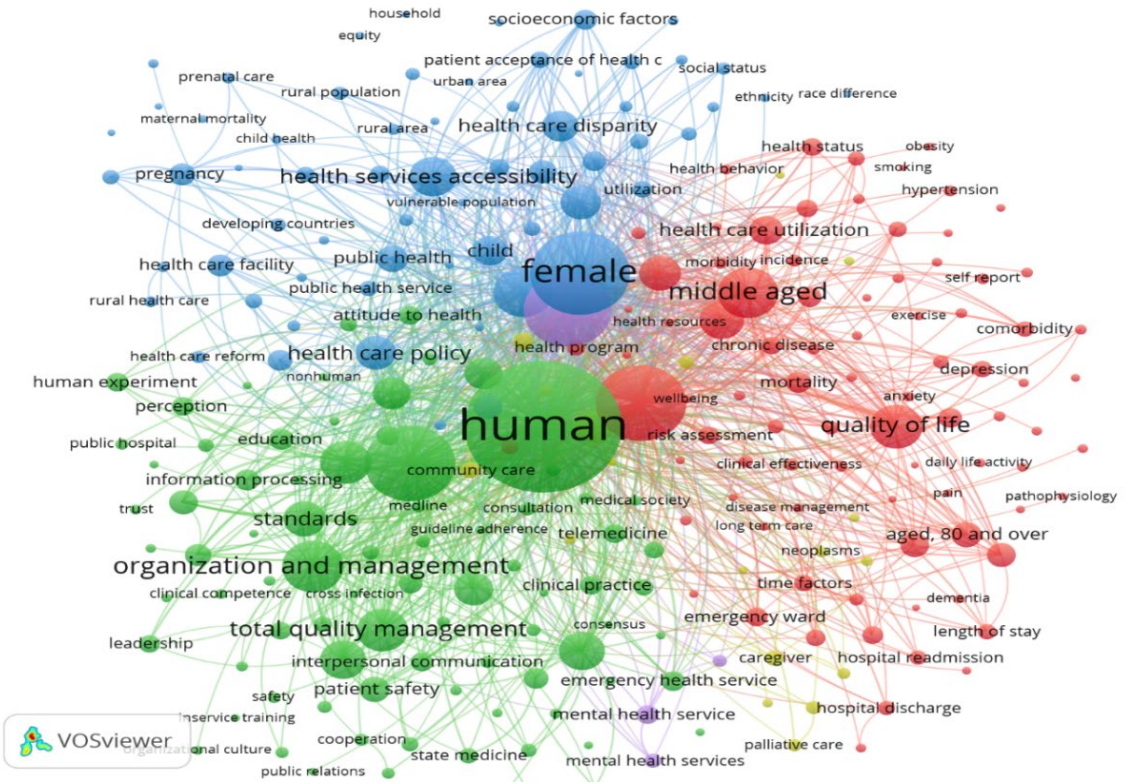

Fig. 4. Map of research themes based on the co-occurrence of keywords in publications referring to healthcare service quality from the SCOPUS database

Source: Elaborated by the author based on the VOS viewer software.

vice provided at care centres is striving to organise and manage its structure to provide good-quality services to satisfy the clients.

The perception of demographic factors (different age and gender groups) is covered in the fourth cluster (Cluster 4), containing 22 keywords. The issue of age is located at the centre of this cluster and connects with different factors, such as the health status (the older the patient, the higher the expectations related to public healthcare service and the greater the effort to be made to provide this service), socioeconomics, patient satisfaction and the time factor.

The last group (Cluster 5) is the least extensive group (21 keywords) that focuses on the methodology and programme evaluation of the quality of service. Nodes of this cluster have relationships with nodes of all map clusters. This group deals with society and its behaviour as well as the responsibility to create a new, safe, educated, healthy population and to ensure full access to public services for all layers of society, including vulnerable groups.

The analysis of each cluster from the Scopus database was based on the keywords identified in research articles. As shown in the map, different combinations of keywords were respected due to diverse research perspectives. Thus, while Clusters 1, 2 and 3 cover the structural perspective and mainly concentrate on the research and description of the quality and its improvement, Clusters 4 and 5 show the regional perspective and contain the analysis of the overall economic level.

Five clusters (Fig. 4) were also identified while conducting a bibliometric analysis of the publications on the basis of healthcare service quality.

It is clear that the central place is taken by the first cluster (Cluster 1), concentrated on people's well-being and quality of life, which is the most extensive group, containing 86 items. One of the recent trends is extended life expectancy, which leads to a prolonged life for disabled people and influences their relationship with their surroundings (Wittenberg et al., 2013). Such factors as chronic diseases, long-term care, and mental diseases are research topics on the improvement of people's health status. Minimising the impact of all risk factors, including obesity, smoking and hypertension, plays a crucial role in the decrease of the morbidity rate and in the strengthening health resources. Together with a lower mortality

rate, daily life activity and avoiding such stressors as depression and anxiety are associated with an improved quality of life, which contributes to the well-being of the population.

Other crucial keywords were covered in the second cluster (Cluster 2), counting 84 elements. It mainly concentrates on the human factor to be considered while organising and managing the system of quality in healthcare services. To provide patients with high-quality medical service, certain standards should be introduced with constant quality improvement. According to the combination of links among elements, interpersonal communication is an important factor for patient safety, tightly connected with total quality management. Consultations, information processing, education, and community care are the most frequent items that are closely associated with the human factor.

The third classified cluster (Cluster 3) involves topics that concern one of the most tightly connected and the most common elements in the network, i.e., the gender factor, mainly female, and counting 63 elements. Cluster 3 deals with global health on the governmental level. This group covers such issues as the disparity in health service accessibility, socioeconomic factors affecting healthcare service accessibility and how health policy is provided. One of the key aims of the Sustainable Development Goals (SDGs) is achieving universal health coverage (UHC), which enables all citizens, including vulnerable groups (women, residents of rural areas, citizens of developing countries, and children) to have access to high-quality healthcare services (Universal Health Coverage, 2019). It is time to introduce a healthcare reform on the availability of equal care. Sets of goals were defined by the World Bank, SDG3, and the World Health Organization (WHO) to be obtained by 2030. One of them requires 80 % of essential healthcare services to be provided to the entire population irrespective of gender, place of residence or economic status (Boerma et al., 2014). In order to ensure sufficient maternal and child health care, women's access to care facilities must be improved. Maternal healthcare helps in reducing maternal and child mortality (Lassi & Bhutta, 2015), explaining the reasons why pregnancy and prenatal care issues are presented in this cluster.

The following cluster (Cluster 4) contains 18 items and is the most dispersed group: its elements are scattered on the whole area of the map. Cluster 4 concerns health care needs and demands; therefore, cluster nodes are connected with ageing (cancer, neoplasm, terminal care) because people over 80 years mainly encounter such diseases. The cluster also covers the topics connected with the human factor (community care and psychology). To create a healthy (psychologically and physically) population, people need to be supported by specialists. The social support issue from this cluster covers community care and links women and the ageing group.

The final cluster (Cluster 5) was comprised of mental health care and had only four keywords which are observed in the analysed map. The mental health service appearing in the context of analyses connects with mental disorders and relates to older people (aged 80 and over). Various stressors linked with older age, such as restricted mobility, an onset of a disease, reduced income having to do with retirement, and social isolation, are believed to predispose mental health issues (National Institute for Health and Care Excellence, 2016). All of these factors may negatively affect people's mental well-being and lead to depression or psychological distress due to their capacity to affect people's feelings, thoughts and activity (Nair et al., 2020; Frost et al., 2019). Therefore, as older age is a vulnerability, it needs to be observed, and mental well-being needs to be promoted.

As in the case of the analysis of the public service quality map, these identified themes of healthcare service quality were based on papers indexed in the scientific database. Every cluster presents a particular field connected with its own layer of the population. Depending on the popularity of one certain area and an increasing trend, i.e., ageing, the higher interest in this area could be noted.

4. Discussion of the results

Consumer satisfaction in public service has received great interest. This popularity is associated with the advantage for organisations increasing their profit from loyal consumers who are satisfied clients. Because of the direct influence of service quality on the level of patient satisfaction, scholars pay significant attention to the definition of service quality and the reasons which lead to its improvement.

Out of all public services, the healthcare service attracts the most significant interest from researchers. Its impact on different spheres on a large scale makes the healthcare sector increasingly more influential on the people's quality of life. According to the bibliometric analysis, researchers studying the quality of public service mostly focus on the healthcare service.

Not only consumers of the healthcare service require well-functioning management and communication. The conducted bibliometric analysis suggested that consumer satisfaction with the total public service depends on maintaining these parameters at a high level. Besides, demography and age also play a significant role in either public service or narrower healthcare service. The quality of life depends on the service received from healthcare providers, and this crucially affects the people's perception of other public services. All people's needs and demands, which relate to social and mental well-being, are a significant part of their life and should not be ignored either by public service or by healthcare service providers. On this account, healthcare service is seen to be closely bonded with public service and vice versa. Therefore, an increased level of consumer satisfaction in the healthcare service significantly contributes to improving the total level of consumer satisfaction.

Unfortunately, due to the absence of a universal definition and different subjects of study in healthcare service, it seems to be difficult to precisely describe all components affecting patient satisfaction in the healthcare field. Nevertheless, it would be useful to know the relevant research themes in service quality to propose a systematic view. Studies conducted on service quality and consumer satisfaction can help to understand the contribution of different elements to the definition of service quality as well as identification of more effective ways to research the topic. Therefore, to organise the information connected to one subject, the quantitative method would be useful. In the era of technology, an enormous amount of information is saved on the Internet. So, it is not surprising that a computerised bibliometric analysis is one of the most common and helpful methods using data mining (Wallin, 2005).

There have already been some bibliometric studies carried out on the topic of service quality; however, they were conducted in different analysis periods and did not provide a comparison. Harith et al. (2020), for example, focused on the service quality in general and did not divide it into some elements as in the case of this study, i.e., public and healthcare sectors. Although Harith et al. also investigated the topic with the VOSviewer program, the analysis concerned a different period, i.e., from 2009 to 2019, with a co-authorship and co-occurrence analysis. It was established that in 2009–2019, the US and China took the lead, compared to US and UK in 2012–2022, respectively. It means that the UK started focusing more on quality, whereas in previous studies, it was not even among the first 15 countries that published most articles in the area of service quality. Harith et al. did not identify the main research perspectives and their contribution to the subject as it has been done in this study.

As the interest in the healthcare service is growing every year, Javed et al. (2021) conducted a bibliometric analysis in this field in 2021, which included publications from 1969 to 2019. Authors limited their search to a document type, i.e., articles, the source type, i.e., journals, and language, i.e., English only. They also used VOSviewer and worked with the Scopus database. A similar analysis was made on co-authorship and co-occurrence. They also analysed the number of publications per year and identified the most influential authors, but the research perspectives have not been identified.

Conclusions

Topics of public service quality and healthcare service quality are widely recognised in the literature in the fields of business, management and accounting and economics, econometrics and finance. More than 25000 articles were analysed in total for the period between 2012 and 2022. A bibliometric analysis was used as a research technique, and the Scopus database was verified. The investigation was made in the field of public (21758 articles) and healthcare (3671 articles) service, where research themes were identified.

Following the inquiry, five research themes were established in both sectors. However, these issues are different in each area. To begin with the public service, customer satisfaction and methods of its estimation was the main research perspective that related to widely spreading service culture and the rivalry of an organisation aiming to attract as many clients as possible. The SERVQUAL method was among the main methods to measure service quality, clearly seen in the second cluster of the public service. The other identified perspective has to do with financial issues, which are necessary for providing high-quality service (including health service) to make people satisfied. As a result, it is certain that there should be an optimal structure and culture in the organisation; consequently, the next research theme relates to this organisational process and includes communication as a necessary way of receiving information and sharing it with all process participants. The final two research themes were linked but were separated into two groups. Both of them reflect the government's

approach to assuring the delivery of high-quality service to people. The first theme relates to demographic factors influencing the public service and determinants for providing this service to clients of different ages and genders. The second theme is related to vulnerable groups, such as children and poverty-stricken people.

When it comes to the quality of healthcare services, five research themes were identified, and some of them were similar to the ones identified for the public service. Nevertheless, compared with the public service, where customer satisfaction was investigated to satisfy clients in different areas of their life, themes in the healthcare sector mainly related to people's health. Therefore, the key issue for the healthcare service quality is in the area of people's well-being, i.e., determinants for the improvement of quality and the longevity of patients, and support to preventive programmes decrease risk factors of chronic diseases. The next research theme identified in this review was the patient perception of healthcare service.

Many literature sources provide investigations into determinants of people's perception, including education and means of communication impacting their attitude towards the healthcare service. Another research theme identified in this study was the availability of care services for vulnerable groups. As in the case of public services, the problem of service access to females or children is also relevant in the healthcare area. Children's mortality and ageing populations necessitate studies on the access to high-quality health service for these groups. The same reasons led to the last two themes. Ageing populations and a wide spread of some specific disorders encourage scientists to analyse the demands and needs of people during their lifecycle, including mental health services, to improve the quality of life for people with mental disorders, which are more likely to occur at an older age.

This study demonstrated an extreme increase in publications in public and in healthcare areas over the last ten years, and this number is expected to grow further. The USA and UK remain the main distributors of these scientific efforts. Some research themes, such as vulnerability, despair, and access to high-quality service, were clusters showing the lowest popularity. However, these topics deserve more attention. It should also be noted that the main methods for measuring the quality of service were SERVQUAL and benchmarking, as clearly presented in the maps of this study.

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Safety and health at the workplace in the context of COVID-19: the case of a dental clinic

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ABSTRACT
Governments of different countries and healthcare organisations working in various areas face enormous challenges when trying to combat the COVID-19 pandemic and protect employees, their families and communities. Workplaces can be high-risk environments in terms of the virus outbreak and transmission. This paper aims to disclose the ways for workplace safety improvement in dentistry in the context of COVID-19. The authors present the theoretical model of workplace safety improvement with regard to COVID-19 infection prevention and control measures. The expectations, fears and tasks of dental employees at their workplace in the context of the COVID-19 pandemic were investigated based on the systematic literature review and the qualitative empirical study conducted in Lithuania. The study disclosed that unmet employee expectations could lead to different kinds of fear; the most common sources of anxiety are linked to a higher risk of getting infected, a lack or misuse of protection measures and inadequately performed work. Occupational risks are closely related to the components of a workplace system. Therefore, it is important to apply a holistic approach to improve workplace safety, enhance work performance and minimise the negative effects on an employee, an organisation, a patient and a society.

KEY WORDS
workplace safety; COVID-19 pandemic; dentistry

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Introduction

The outbreak of coronavirus disease (COVID-19) in Wuhan, China, has evolved rapidly into a public health crisis and spread exponentially worldwide (Ather et al., 2020). COVID-19 is an international public health emergency announced by the World Health Organization (WHO) in January 2020 and declared a pandemic in March 2020 (Stangvaltaite-Mouhat et al., 2020; Khunti et al., 2021). Despite the global efforts to stop the spread of the disease and

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the advantages afforded by vaccination, the number of cases is still high leading to the emergency status in the entire health system, including dentistry (Ather et al., 2020; Consolo et al., 2020; Agius et al., 2021). The pandemic did not bypass Lithuania either. To date (23 February 2022), Lithuania has recorded 879371 confirmed cases of COVID-19 and 8316 deaths, a 14-day notification rate of newly reported COVID-19 cases per 100 000 population was 3647.4 (COVID-19 in Lithuania). The pandemic has had a direct impact not only on health but also on markets, supply (production of goods and services), demand (consumption and investment) and the ways of work. Governments, employers and workers face enormous challenges when combating the COVID-19 pandemic and protecting their staff, families and communities (Ingram et al., 2021; ILO, 2020).

The current pandemic is a hot topic which has attracted considerable academic attention in different areas of science. The World Health Organization, the International Labour Organization (ILO), and national authorised healthcare organisations expressed great concern and proposed measures to manage the COVID-19 pandemic. A growing interest in COVID-19 was demonstrated in numerous research works conducted in different countries. Scientists, WHO and ILO examined employee safety behaviours and workplace safety management practices (Lee, 2022; Vu et al., 2022), prevention and control measures in workplace settings (Agius et al., 2021; Ingram et al., 2021; ILO, 2020; COVID-19: Occupational health and safety for health workers, 2021), the issues of workplace preparedness (Stangvaltaite-Mouhat et al., 2020, Andújar Trabazos et al., 2021), a psychological impact of the COVID-19 pandemic (Stangvaltaite-Mouhat et al., 2020; Uhlen et al., 2021), risks to healthcare workers (Khunti et al., 2021; Strain et al., 2021), employee satisfaction (Uhlen et al., 2021), workforce confidence (Liu et al., 2022), the fear of being infected and fired (Chen et al., 2022), and other work-related changes when dealing with the pandemic. Workplaces can be high-risk environments in terms of SARS-CoV-2 outbreaks and subsequent community transmissions (Ingram et al., 2021). The pandemic puts extraordinary pressure on healthcare professionals and negatively affects the delivery of health care services globally (Uhlen et al., 2021). Ensuring safety and health at work remains a top priority for organisations (Chen et al., 2022).

Although the scientific community has widely analysed the issues related to the COVID-19 pandemic and its prevention, this topic is still relevant as the pandemic is not going away and will potentially change the nature of work and workplace safety. There is still a literature gap and the need to understand how occupational risks affect a workplace system and what effects these risks have on an employee, a patient, an organisation and a community. The purpose of this paper is to explore the relationship between occupational risks and workplace safety in dentistry. Additionally, the authors have investigated the expectations, fears and tasks of dental employees at their workplace in the context of the COVID-19 pandemic. Based on the research results, specific recommendations regarding workplace safety in the area of dentistry were provided. The paper employs the systematic literature review and the qualitative empirical study conducted in Lithuania in 2021–2022.

1. Literature review

Organisations adopt occupational health and safety management systems to control the hazards and ensure a safe work environment and the health of their employees. During this pandemic, organisations emphasise workplace safety to mitigate health risks and manage the problems specific to the crisis (Vu et al., 2022). Dentists face a heightened risk of infection with their proximity to the oral cavity (Liu et al., 2022). The dental practice involves close contact with a patient and the use of rotating and surgical instruments that generate a visible spray containing droplets of water, saliva, blood, microorganisms and other debris (Stangvaltaite-Mouhat et al., 2020; Uhlen et al., 2021; OSHA, 2022). Dental professionals can deal with patients with a suspected or confirmed infection and need to work diligently not only to provide care and treatment but also to prevent the spread of infection (Ather et al., 2020). Given the risks, a dental office may become a site of cross-infection if adequate precautions are not taken (Uhlen et al., 2021).

Healthcare workers experience discomfort and occupational hazards that put them at risk of illness and even death from exposure to COVID-19. According to the guide (2021) issued by the World Health Organization (2020) and the International Labour Organization, these occupational risks include occupational infections with COVID-19; skin disorders and heat stress from the prolonged use of personal protective equipment (PPE); exposures to toxins because of the increased use of disinfectants; psychological distress and chronic fatigue. The use of additional protection measures requires additional time,

burdens workers and reduces their productivity. Risk mitigation, workplace safety and employee well-being improvement in the healthcare sector require risk assessment, well-coordinated and comprehensive infection prevention and control measures, occupational health and safety management, and mental health and psychosocial support (WHO, 2020; ILO, 2021). On the contrary, insufficient health and safety measures can lead to increased illness rates among healthcare workers and patients, high rates of absenteeism, reduced productivity and deteriorated quality of health services (ILO, 2020).

Jahangiri et al. (2013) described risk perception as "an individual's subjective judgment about the characteristics and severity of risks". Risk perception is one of the characteristics of a person that affects an individual's behaviour, so a misperceived risk leads to insecurity in the workplace; therefore, investigating risk perception plays an important role in ensuring workplace safety (Jafari et al., 2019) and individual work output (Shan et al., 2022; Szydło & Grześ-Bukłaho, 2020).

The fear of COVID-19 as a significant mental health moderator was analysed by Blanuša et al. (2021). The fear of infection influences the presence of job insecurity and work-related distress. The results of the research conducted among Italian dentists confirmed the relationship between job insecurity and depressive symptoms (Gasparro et al., 2020). Eman et al. (2021) investigated that the fear of COVID-19 was negatively associated with job satisfaction. Anxiety about possible COVID-19 infection

Tab. 1. COVID-19 infection prevention and control measures

Area/ Direction	IPC measures	Description
Prevention and deterrence	Surveillance and response	COVID-19 symptom monitoring, strategies to screen or test individuals; contact tracing and testing of close contacts; quarantine; self-isolation of confirmed cases
	Physical distance	Organising work in a way that allows for physical distancing between people; when possible, using phone calls, emails or virtual meetings rather than face-to-face meetings; introducing working shifts to avoid large concentrations of workers in the facilities at any given time
	Changes in work arrangements	Facility zoning, entrance restrictions; changes in assignments for high-risk workers; facility shutdown, expanded access to paid sick leave, sickness benefits and parental/care leave
	Environmental adjustments	Improving airflow and ventilation; use of easily decontaminated physical barriers or partitions between patient treatment areas
	Teledentistry	Remote facilitation of dental treatment, guidance and education via the use of information technology instead of direct face-to-face contact with patients for non-emergency dental situations
Hygiene and PPE	Hygiene, cleaning and disinfection	Promoting good respiratory hygiene at workplaces; regular disinfection of common areas; promoting a culture of handwashing, cleaning the surfaces of desks and workstations, telephones, keyboards and work objects; application of UVC light for disinfecting surfaces of equipment, operating rooms and PPE
	Appropriate PPE	Selection and provision of appropriate PPE: masks and respirators for respiratory protection, goggles and shields for eye protection, gloves for hand protection, and gowns for body protection; providing closed bins for hygienical disposal of PPE
Administrative	Education and training	Education and training on IPC measures; training on the correct use, maintenance and disposal of PPE
	Communication and signage	Maintaining regular communication with workers to provide updates on the situation in the workplace, region or country; communication and signage
	Policy and control	Assurance of adequate resources for IPC; appropriate infrastructure; development of clear IPC policies; appropriate triage and placement of patients; extending operational hours or reducing the number of appointments; adequate staff-to-patient ratios
Combined	Combined measures	Combined application of different types of measures

Source: Elaborated by the author based on the ILO report (2020), Stangvaltaite-Mouhat et al. (2020), Khunti et al. (2021), Ingram et al. (2021), Vu et al. (2022), OSHA (2022), Seladi-Schulman & Can (2022), Ghai (2020).

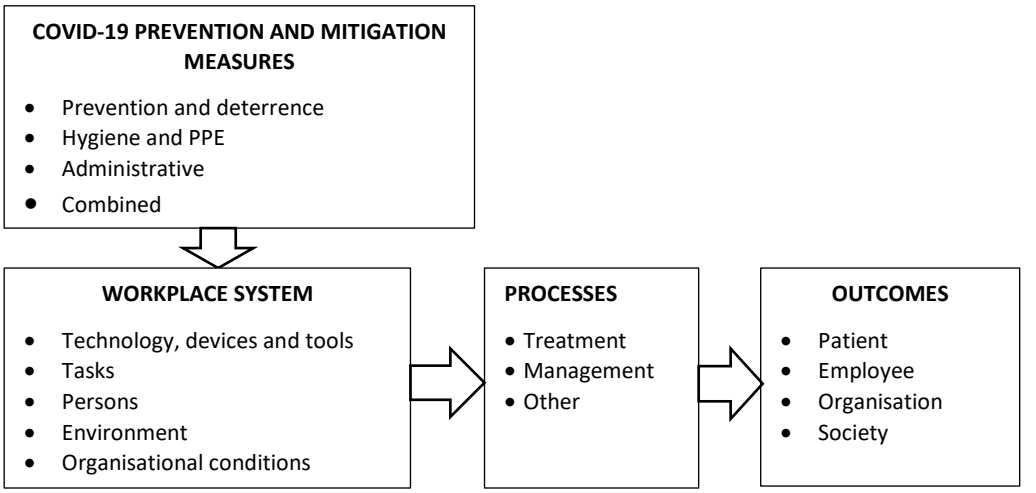

Fig. 1. Theoretical model of workplace safety improvement in the context of COVID-19

Source: Elaborated by the author based on Carayon et al. (2006).

in the workplace is an important issue in occupational mental health. The effects of the COVID-19 pandemic on workplaces may influence the changes in employee anxiety. Anxiety related to COVID-19 caused distrust and anger among employees. The anxiety about being infected with COVID-19 in the workplace strengthens the relationship between job demands and psychological distress (Eguchi et al., 2021)

A safe workplace, access to the appropriate equipment and implementation of the appropriate infection control measures are critical in reducing the fear of infection and the feeling of instability reported by dental professionals working with patients during the pandemic outbreak (Uhlen et al., 2021). Various measures can be taken to reduce the risk of contagion between dental professionals and patients. Based on the ILO report (2020) and other literature sources (Stangvaltaite-Mouhat et al., 2020; Khunti et al., 2021; Ingram et al., 2021; Vu et al., 2022; OSHA, 2022; Seladi-Schulman & Can, 2022; Ghai, 2020), Table 1 summarises the main COVID-19 infection prevention, control (IPC) measures, and provides their description.

The measures in Table 1 are divided into four groups, covering prevention and deterrence, hygiene and PPE, and administrative and combined measures. A combination of preventive and hygiene measures with management's commitment to safety and employee involvement is extremely important to ensure workplace safety.

Carayon and Smith (2006) developed a work system and patient safety model that includes a work system (persons, tasks, tools and technologies, physical environment, organisational conditions), processes and outcomes. Based on this model and literature analysis (Ciarniene et al., 2017; WHO, 2020), the authors of this article present a theoretical model of workplace safety improvement with regard to COVID-19 infection prevention and control measures (Fig. 1).

A dental practitioner performs different tasks by using a variety of technologies, medical devices and tools. These tasks are performed in a specific physical environment and under certain organisational conditions. The five components of the work system interact and affect each other (Carayon et al., 2006). The workplace system affects the process performance, which, in its turn, makes an impact on patient, employee and organisation outcomes (Carayon et al., 2006). In the context of COVID-19, the changes in different aspects of the work system had to be made by adding new safety procedures, monitoring, personal protective equipment, environmental adjustments, regular disinfecting, changes in work arrangements, and altering patient scheduling and staffing to meet safety recommendations (Liu et al., 2022).

Without a doubt, these changes affect treatment, management and other processes, and it all affects the physical and mental health of employees (skin disorders and heat stress from the prolonged use of PPE, exposures to toxins because of the increased use of disinfectants), job satisfaction and stress, productivity and organisational performance, quality and availability of healthcare services, and patient safety. Patient, employee and organisational outcomes impact society in general, thus contributing to the

prevention of the infection or, conversely, promoting its spread.

2. Research methods

The study was conducted in a dental clinic located in Kaunas city, Lithuania. The clinic provides therapy, prosthetics, endodontic, periodontal, orthodontic and oral hygienist services. The clinic has 28 employees, including administrative staff. The study was conducted as a part of the project "Prevention of airborne transmission of respiratory viruses (COVID-19) in dental services". The project aims to develop a tool to stop the spread of the COVID-19 virus and to safely provide dental services during the global pandemic. To achieve the aim of the project and develop an innovative product, R&D activities were implemented. The project was launched in January 2021 and is due to end by April 2022. The project is funded by the European Regional Development Fund as part of the European Union's response to the COVID-19 pandemic.

Qualitative interviews were used to collect the empirical data. According to Kallio et al. (2016), semi-structured interviews are versatile and flexible; they ensure reciprocity between an interviewer and a participant and allow for improvising when asking further questions based on a participant's answers. The purpose of qualitative research is to know, understand and describe social phenomena, people's experiences, and social interactions that take place in a certain environment and to reveal how research participants make meaningful experiences, interactions and how they behave in their everyday life (Žydžiūnaitė & Sabaliauskas, 2017, Czerniawska & Szydło, 2020). This method makes it possible to obtain detailed opinions and assessments about the ongoing phenomena and gain an insight into the respondents' daily professional experience at the workplace. A qualitative interview is based on open-ended questions. It is expected to provide the answers as broad, comprehensive and open as possible, formulated and presented by research participants, reflecting their perspective (Gaižauskaitė & Valavičienė, 2016).

Sample size. Achieving data saturation is important in qualitative research. Various sources recommend different sample sizes, which may range from 5 to 60. According to Hennink and Kaiser (2022), data saturation can be achieved even with a "small" sample, such as 9–17 interviews. This research involved a sample of nine respondents. The respondents were selected by using the principle of targeted sampling, while the principle of random sampling was rejected. The respondents with personal experience, responsibility, characteristics and social contexts allowing them to answer the interview questions with appropriate accuracy were sought. The interviews with the staff were approved by the management of the dental clinic; staff participation was voluntary. The research involved one oral hygienist, one endodontist, five dentists, one orthopaedist and one periodontist; one respondent was male, and eight were female. All the respondents had at least three years of work experience in the area of dentistry. The research process is presented in Fig. 2.

The internal marketing theory claims that employees are internal customers in each organisation (Huang & Rundle-Thiele, 2014). The Value Proposition Canvas approach was used to understand how to reconcile workplace safety requirements with internal customer needs. According to Adams (2015), a questionnaire is not the best term for the compilation of semi-structured interview questions; therefore, the agenda for the interview guide was developed based on the customer profile and covered three categories of questions related to internal customer jobs, pains and gains. The questions in the section "Gains" aimed to explore the expectations of the employees as internal customers at the workplace and disclose what creates the employee value during the time of the Covid-19 pandemic. The questions in the section "Pains" aimed to reveal the negative experiences, emotions and perceived risks that the employees can face at the workplace. Finally, the questions in the section "Jobs" focused on daily task performance

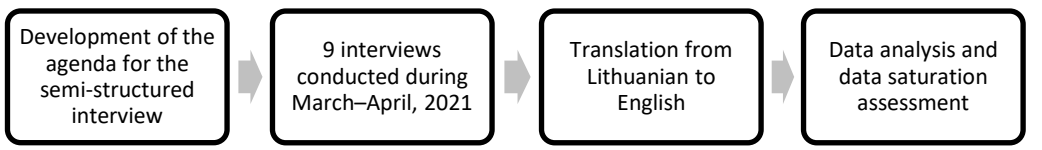

Fig. 2. Flow diagram of the research process

from the functional, social and emotional perspectives. The interviews were transcribed following confidentiality obligations not to reveal the identity of the respondents. The data were processed by interpreting, systematising, analysing and categorising the answers. The evidence citations are presented in categories and subcategories.

3. Research results

The analysis of the employee expectations revealed that the respondents expected to feel safe, protect themselves and others from viruses and save time for task performance (Table 2).

According to the respondents, an effective and convenient protection measure against airborne viral diseases would allow the tasks to be performed efficiently and would reduce employee anxiety and loss of time. It is obvious that unmet employee expectations can lead to different kinds of fear. The most common sources of anxiety are linked to a higher risk of getting infected, the lack or misuse of protection measures and inadequately performed work. Compliance with safety requirements and additional measures results in a waste of time and raises the probability of mistakes at the workplace (Table 3). The respondents' answers disclosed the necessity for innovative specific devices and combined measures.

Day-to-day workplace operations involve compliance with specific requirements, safety and security measures that cause inconvenience to employees. The demands of day-to-day operations, in their turn, raise employee fears, create discomfort, increase the likeli-

Tab. 2. Links between employee gains/expectations and perceived occupational risk in the workplace

Employee gains/expectations		
Subcategory	**Statements**	**Links with risk**
Employee expectations	[R2] "Protect me and others from viruses" [R1], [R4] "Safe work environment for a doctor and a patient" [R6] "Work safely without the risk of infection with the virus" [R8] "… return to regular hygiene requirements. To eliminate the need for protection measures" [R2] "Work both safely and ergonomically" [R3] "Work in a safe environment" [R4,5] "Eliminate the need for coveralls, etc." [R6] "Eliminate the risk of infection working regularly, with fewer protection measures" [R7]"Safe" [R8]"...work not constrained by adverse circumstances" [R9] "...work comfortably, with unrestricted movements" [R9] "…feel free working with patients, especially during the procedures with a high prevalence of pathogens, not to feel the risk of infection or bringing viruses home" [R1] "Time-saving working without forced breaks. Comfortable work without wearing so many protective measures" [R2] "I would be glad about both time and money saved" [R9] "Time-saving working without forced breaks. Improved well-being at work, knowing that the risk of infection has been significantly reduced or eliminated" [R6]"Ensuring safety would reduce the risk of infection, save time and eliminate the need for ventilation interruptions between patients; patients would feel safer, they would not need to pay extra for protection measures"	• Occupational infections with COVID-19 • Psychological distress • Exposures to toxins because of the increased use of disinfectants • Skin disorders • Chronic fatigue • Extra time
Specific measures/ devices against the virus	[R1] "A virus-killing device" [R7] "A device preventing the spread of aerosols" [R4], [R5]"An effective measure for airborne viral diseases" [R6] "the ability to wear fewer protection measures and work at the regular rhythm"	• Extra time

Tab. 3. Links between employee pains/fears and perceived occupational risk at the workplace

Employee pains at the workplace		
Subcategory	**Statements**	**Links with risk**
Anxiety sources	[R1] "Risk of infection" [R2] "Work feeling heat discomfort, pressure, rubbing, etc. caused by protective measures" [R3] "It is hot to work wearing all protective measures, so it is uncomfortable" [R6] "When there is a lack of protective measures, when someone does not follow the protocol, when an assistant forgets to give a rinse, respirators pull ears hard, wearing optics and a shield is uncomfortable, but without wearing a shield, I am not sure if I sufficiently protect myself; it is hot to work wearing all protective measures" [R8] "Infection or inefficiency of the current protective measures" [R2] "Fear to get infected and infect others (patients, colleagues)" [R9] "Ineffective disinfection" [R7] "Fear of poorly performed work" [R9] "Time-saving working without forced breaks. Improved well-being at work, knowing that the risk of infection has been significantly reduced or eliminated" [R6]"Ensuring safety would reduce the risk of infection, save time and eliminate the need for ventilation interruptions between patients; patients would feel safer, they would not need to pay extra for protection measures"	• Occupational infections with COVID-19 • Psychological distress • Exposures to toxins because of the increased use of disinfectants • Skin disorders
Time losses	[R1], [R4], [R5] "Disposal of protective equipment, dressing and undressing" [R2], [R3] "Caused by safety measures, dressing and undressing personal protective equipment, its collection/utilisation after use" [R6] "Changing clothing during the procedure if you need to go to another room, consult your colleagues; if you are in protective equipment, you cannot do that, which impedes work (you need to undress and then dress again)"	• Extra time • Chronic fatigue
Mistakes	[R9] "Tired of high requirements, employees start not to comply with them" [R2] "Employees incorrectly wear PPE, wear inappropriate PPE or do not wear it at all. They take it off unsafely after use"	• Occupational infections with COVID-19 • Chronic fatigue

Tab. 4. Links between employee jobs and perceived occupational risk in the workplace

Employee jobs at the workplace		
Subcategory	**Statements**	**Links with risk**
Requirements	[R1] "Observe high hygiene requirements" [R7] [R8]"Observe the same requirements, understand and support each other" [R3], [R4] "If the purpose is infection control, employees must observe the established requirements"	• Occupational infections with COVID-19 • Psychological distress • Exposures to toxins because of the increased use of disinfectants • Skin disorders
Safety and security measures	[R2], [R3] "Protect yourself and others" [R2], [R3] "Wear PPE" [R2], [R3] "Wear PPE safely and comfortably – wear fewer measures or use highly protective equipment" [R6] "Wear extra protection, allow extra time for ventilation" [R9] "…lack of PPE at the beginning of the pandemic"	• Occupational infections with COVID-19 • Psychological distress
Inconveniences and discomfort employees want to avoid	[R4], [R5] "A doctor feels uncomfortable wearing three layers of PPE" [R8] "Wearing uncomfortable PPE, waste of time putting it on and taking off" [R4], [R5] "Stress and discomfort" [R2], [R3] "Mistakes" [R6] "Prevent time losses doing everything to protect against the virus and reduce high costs	• Occupational infections with COVID-19 • Skin disorders • Extra time • Psychological distress • Chronic fatigue

Tab. 5. Manifestation of occupational risk in the workplace system

	Workplace System				
	Technology, devices, tools	Tasks	Person	Environment	Organisational conditions
Occupational infections with COVID-19	x	x	x	x	x
Skin disorders and heat stress from the prolonged use of PPE	x		x	x	x
Exposures to toxins because of the increased use of disinfectants		x	x	x	x
Psychological distress		x	x	x	x
Chronic fatigue		x	x	x	x
Extra time needed for PPE and disinfection	x	x	x		x

hood of mistakes, and require extra time to perform direct tasks (Table 4).

The workplace system aims to deliver value and outcomes for different stakeholders, such as patients, dental professionals and organisations. The COVID-19 pandemic affects all the components of the workplace system. Different types of occupational risks can manifest in relation to medical devices, tools and technologies, tasks, persons, environment and organisational conditions (Table 5).

Occupational risk affects the entire workplace system. Technology, devices and tools have to be disinfected, which requires extra time, effort and performance of extra tasks, such as regular disinfection of common areas and surfaces of work objects, use of appropriate PPE and their hygienical disposal and regular ventilation of premises. All of this requires more time for task performance and leads to a reduced number of appointments. Extra tasks raise employee workload and decrease productivity, organisational performance and quality of healthcare services. Consequently, all these risks negatively affect employee motivation and job satisfaction, leading to chronic fatigue and psychological distress. Occupational infections with COVID-19 may affect physical and mental employee health and cause the necessity to reorganise processes, work schedules and patient care procedures. To ensure workplace safety, it is important to educate and train employees on the correct use of IPC measures and PPE, maintain regular communication and update the measures applied in response to the COVID-19 situation. Moreover, it is important to look for new opportunities and consider innovative technologies for virus prevention and deterrence.

4. Discussion and conclusions

This paper investigates the effects of the COVID-19 pandemic on workplace safety when providing dental care services. The research revealed the occupational risks encountered by employees in the workplace and provided insight into how these risks affect employees' daily activities. In terms of a theoretical contribution, this study expanded previous findings of Carayon et al. (2006), proposing that the work system is composed of five components — a person, tasks, tools and technologies, the physical environment and organisational conditions — and plays a key role in delivering smooth processes and providing employee, patient and organisation outcomes. In the context of COVID-19, prevention and mitigation measures and the component of society were integrated into the work system and patient safety model proposed by Carayon and Smith (Carayon et al., 2006). In line with the current study, workplace safety can be ensured by adjusting the components of the work system. COVID-19 prevention and mitigation measures cover the areas of prevention and deterrence, hygiene and PPE, and administrative and combined measures. A combination of these measures affects all components of the workplace system by generating extra tasks and changes in the work environment and organisational conditions. Consequently, these changes affect treatment, managerial and auxiliary processes, which, in

turn, impact physical and mental employee health, job satisfaction, motivation and productivity. Moreover, new requirements for organisational performance arise when providing healthcare services for patients. Dental care organisations also contribute to social outcomes by preventing the infection or, conversely, by spreading it.

It should be noted that the results of the empirical research fit the theoretical background in this particular area. The empirical research focused on workplace safety and work experience of dental professionals in the context of COVID-19. The study framework was based on the theoretical model and the main occupational risk defined by the WHO. The research revealed that dental professionals face the following occupational risks: occupational infections with COVID-19, skin disorders and heat stress from the prolonged use of PPE, exposures to toxins because of the increased use of disinfectants, psychological distress, chronic fatigue and disinfection. Occupational risk management, in many cases, requires extra tasks and extra time.

Similar to previous findings (Stangvaltaite-Mouhat et al., 2020), this research revealed that dental professionals note their expectation to work safely and protect themselves, their colleagues and patients. Workplace safety and lower risks of infection would allow to save time, eliminate the need to have ventilation breaks and would make patients feel safer. Access to adequate PPE is considered to be one of the major protective factors in mitigating the fear of infection and illness among dental care professionals. In terms of anxiety sources, interviewees disclosed the fear of becoming infected if protection does not work properly and the discomfort of wearing different PPE, which also causes skin disorders and requires extra time; these stressors were reported to lead to chronic fatigue and psychological distress.

Similar findings concerning psychological distress and chronic fatigue were provided by Uhlen et al. (2021), Consolo et al. (2020), and Stagvaltaite-Mouhat et al. (2020). In addition, employees were worried about the probability of mistakes and their impact on the quality of dental services. The interviewees emphasised the importance of following specific guidelines to reduce the spread of infection. Specific guidelines refer to the procedures and measures that have to be implemented when providing dental care and treatment services. This confirms the findings provided by Stagvaltaite-Mouhat et al. (2020). At the same time, in some cases, specific guidelines and strict requirements can make employees tired, less motivated and less satisfied. Based on research results, occupational risks are closely related to the components of the workplace system. Therefore, it is important to apply a holistic approach to improving workplace safety (Khunti et al., 2021), ensure security and health, enhance work performance and minimise the negative effects on an employee, an organisation, a patient and a society.

While the findings offer theoretical contributions and practical insights, the limitations of the study are also worth mentioning. The major limitation of this research is the consideration of the case of a single dental clinic, which led to relatively small sample size. Although data saturation was achieved, further studies could focus on larger-scale research in this area.

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Impact of the COVID-19 pandemic disruptions on container transport

Katarzyna Anna Kuźmicz

ABSTRACT
The COVID-19 pandemic caused unprecedented disruptions in the global economy, and container transport as a predominant means of the goods flow in global supply chains. Different measures employed worldwide to limit the virus spread, such as restrictions and quarantines on border crossings, port staff, container ships, transhipment terminals and the inland transport sector, created a colossal management challenge and caused a domino effect in delays. Consequently, it led to blank sailings and enormous rises in freight transport prices, the lack of supply reliability and shifts between different means of transport. These delays, enhanced by the Suez Canal blockage, exacerbated an already acute problem of the empty container shortage in the market. This paper aims to provide an in-depth overview of the COVID-19 pandemic's impact on container transport and underline ways to increase resiliency against future disruptions. The research included a literature overview and formulation of recommendations. The paper contributes to the broad research of container transport management and provides insights for practitioners responsible for transport planning and disruption management.

KEY WORDS
container transport, pandemic, COVID-19, Suez Canal, empty containers, blank sailing

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Introduction

Container transport has a leading position in the carriage of goods as it enables their seamless transfer to different transportation modes. The standardisation of containers and their compatibility with transhipment equipment ensures the fast and undisturbed flow of goods. The increase in consumption and globalisation turns container transport into a dynamically developing field. The tendency to build increasingly larger containerships (over 23000 TEU)

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pressurises ports and transhipment terminals to increase their efficiency (Pesch & Kuźmicz, 2020). Some predictions insist that by 2030, considering the current infrastructure of port terminals, ports in Asia, Western Europe and Oceania will possibly operate under conditions extremely close to their capacity limits and in many cases, they will be unable to manage the container flow (Digiesi et al., 2019).

However, 2020 and 2021 brought unforeseen disruptions, and logistics managers met unprecedented challenges. Although problems accumulated by the pandemic were often familiar, they rose in large numbers and scales, unearthing the issues in need of urgent attention.

The pandemic of the infectious disease, COVID-19, caused by the coronavirus SARS-CoV-2, started in November 2019 in Wuhan city in central China and was declared a pandemic by the World Health Organization (WHO) on 11 March 2020. The disease spread to all continents, affecting nearly 248 million people, with over 5 million deaths (Worldometers, 2021). The pandemic disrupted people's lives globally, affecting the world's economy, trade and transport. Internationally, measures have been taken to prevent the spread of the infection. Travel has been restricted, and quarantines and curfews were imposed. Some countries closed their borders or introduced restrictions on border traffic. The pandemic continues, but steps are being taken to restore the economy to its pre-pandemic state gradually. Container transport is closely linked to the developments in the global economy, production and consumption. As such, container port analysis can provide useful insights into underlying macroeconomic trends. During the first 31 weeks of 2020, container vessel port calls varied by region. Globally, container ship calls started to fall below 2019 levels around week 12 (mid-March 2020) and gradually recovered around week 25 (third week of June). These timelines correspond to the beginning of the pandemic. The gradual recovery since June reflects the easing out of lockdowns in some countries (UNCTAD, 2021a).

According to UNCTAD (2021a), the number of shipping services, weekly port calls, shipping operators, deployed container ships capacity and direct calls declined because of the different pandemic rates (Table 1).

The coronavirus spread in China, causing factory stoppages and, finally, downtimes at ports. In combination with the Chinese New Year celebrations, which influence delays in production and delivery on a regular basis, the full-scale delays became very disruptive. The expectation at the beginning of the pandemic was that container transport would experience a sharp fall; however, eventually, as people were staying at home due to restrictions, the demand was supposed to increase due to redecorations, the purchase of electronics, furniture, etc. Later, the lessening of the restrictions caused another rise in the third quarter of the year 2020. The increased demand and delays in transportation resulted in a sharp increase in container transport rates. The lowest relative increase of container freight rate was recorded on the Asia-East coast North America route (+63 %), from China to South America, 443 % higher than the median for this route (UNCTAD b). The justification is that ships

Tab. 1. Percentage change of shipping connectivity components between Q1 & Q2 2020 – Q1 & Q2 2019 in major container ports in developed countries

	Shipping Services		Weekly Port Calls		Shipping Operators		Max TEU capacity		Deployed Capacity		Direct Calls	
	Q1	Q2	Q1	Q2	Q1	Q2	Q1	Q2	Q1	Q2	Q1	Q2
Los Angeles	↓	↓	↓	↓	↓	↓	-	↑	↓	↓	↑	↓
Long Beach	↑	↓	↑	↓	↑	↓	↑	↑	↑	-	↑	↑
NY&NJ	↑	-	↑	-	-	↑	-	↑	↑	↑	↓	↓
Rotterdam	↓	↓	-	↓	↓	↓	↑	↑	↑	↓	↓	↓
Antwerp	↓	↓	↓	↓	↓	↓	↑	-	-	↓	↓	-
Hamburg	-	↓	-	↓	↓	↓	-	↑	-	↓	↓	↓
Bremerhaven	↓	↓	↓	↓	↓	↓	↑	↑	↓	↓	↓	↓
Piraeus	-	-	-	↓	-	↑	-	-	-	↓	-	↓
Felixstowe	↑	↑	↑	↑	-	↑	↑	↑	-	↑	↑	↑
Marsaxlokk	↓	↓	↓	↓	-	↓	↑	↑	↓	↓	↓	↓
Melbourne	↓	↓	↓	↓	↓	↓	↑	↑	↓	↓	↓	↓
Sydney	↓	↓	↓	↓	↓	↓	↑	↑	-	↑	↓	↓

Memo ↓ $R < -2\%$ -- $-2\% \leq R \leq +2\%$ ↑ $R > +2\%$

Source: (UNCTAD, 2021a).

and containers were engaged longer on lengthier routes. The rise of containerised freight rates is presented in Fig. 1.

This paper presents the broad spectrum of the pandemic's impact on container transport (Fig. 2). The most important discussed aspects include the shortage of empty containers, blank sailings, disruptions in ports and inland transport, increase in prices in many domains, the lack of reliability of supplies, shifts between transport modes and production delays. These problems have been exacerbated by the Suez Canal blockage. The paper is concluded with the

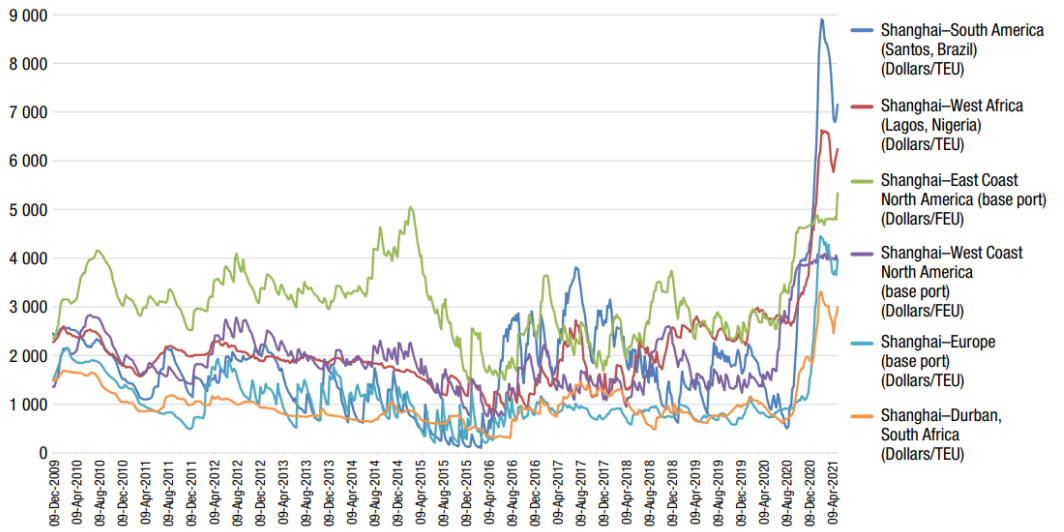

Fig. 1. Rise of containerised freight rates (UNCTAD calculations based on data from Clarkson Research Shipping intelligence Network Time Series)
Source: (UNCTAD, 2021b).

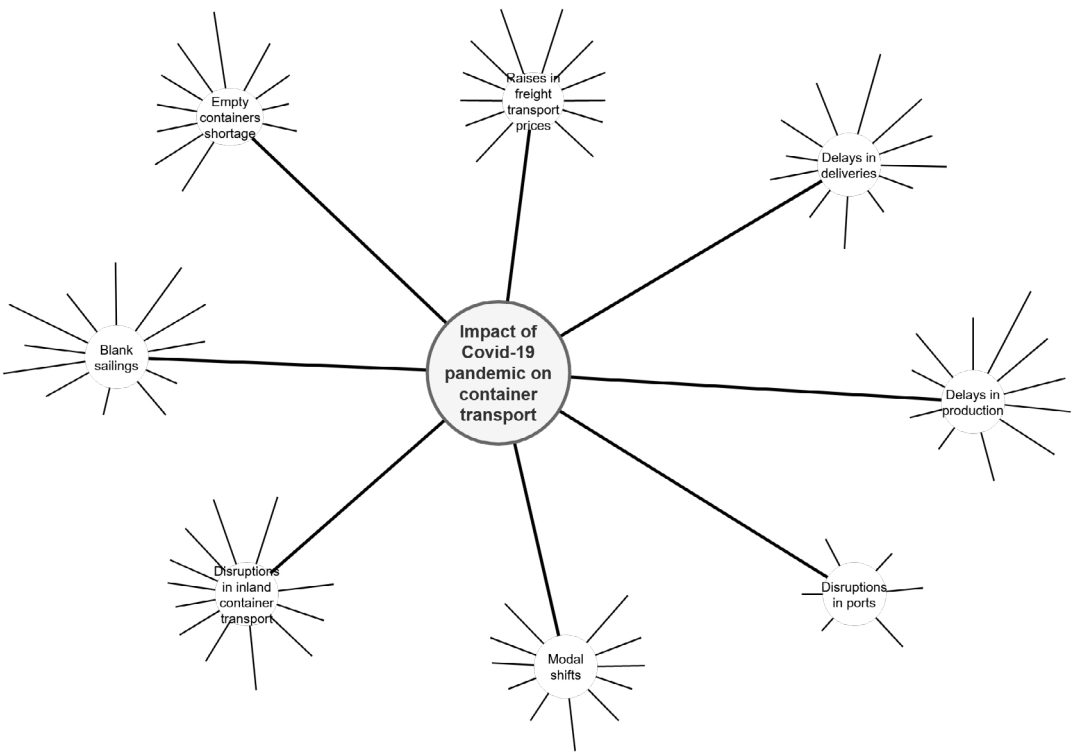

Fig. 2. Spectrum of the pandemic influence on container transport

analysis of the crucial areas needing development to ensure higher resiliency of the container supply chain in the future from two perspectives: customers and transport providers.

1. The areas of the influence of the pandemic on container transport

The pandemic exacerbated the persistent problem of intermodal transportation, namely, empty container management. The relocation of empty containers is a topical issue in scientific research. Kuźmicz and Pesch presented an in-depth study of the problem and approaches to its modelling (Kuźmicz & Pesch 2017; Kuźmicz & Pesch, 2019). The global trade imbalance and the predominance of export or import oriented regions result in the imbalance in container availability. Export-oriented regions, such as China, lack empty containers to be filled with exported goods, whereas import-oriented regions, such as many of the EU countries, receive many full containers but do not have the potential to fill them with products to be exported. This results in the problem of empty repositioning of containers or keeping them and waiting for future demand. The empty container problem is essentially their transportation cost which is close to the cost of full containers.

Empty containers do not generate revenues and are rarely filled with low priority goods, such as paper for recycling, metal or electronics rubbish or other waste that was frequently shipped from Europe to Asia in the past (Kuźmicz & Pesch, 2019). The imbalance of containers shipped in both directions, Europe–Asia, is clearly visible in Table 2.

The difference between supply and demand and ship utilisation in both directions is significant. The demand is nearly double westbound, which clearly explains the problem of empty container imbalance.

The storage of empty containers in a port also involves labour and equipment (cranes, straddle carriers, AGVs, reach stackers, front stackers, etc.). Minimising container movements is not only an issue of cost reduction as it also contributes to the reduction in congestion at and around seaports and inland container terminals and limits detrimental effects to the environment.

The domino effect of delays in maritime transport, ships stacked in waiting at ports under quarantines, reduced staff and safety precautions, and isolated ship crews resulted in a dramatic shortage of empty containers since they were trapped in the prolonged maritime and inland transportation. There was also a shortage of containerships.

All vessels in appropriate technical condition were used. The rise in demand also resulting from the pandemic caused massive disturbances at ports and in inland-bound transport. Ships had to wait for about 10–14 days before being allowed to enter the port.

Hapag Lloyd reported that in January 2021 alone, their ships were 170 hours late on average on the most frequented Far East routes, while on trans-Pacific routes, delays reached 250 hours on average (DW, 2021).

As a result of all delays, carriers introduced blank sailing, i.e., skipping port calls (UNCTAD, 2021a) and not picking up containers at ports. The transportation preference of full to empty containers is a common practice, but under these critical circumstances, blank sailings exacerbated the empty container shortage.

Tab. 2. Asia–North Europe: estimated monthly supply/demand of containers

Period	Supply (thousands of TEU)		Demand (thousands of TEU)		Ship utilisation (%)	
	Westbound	Eastbound	Westbound	Eastbound	Westbound	Eastbound
Sept.2017	917	674	818	407	89%	60%
Oct. 2017	922	679	742	419	80%	62%
Nov. 2017	919	670	731	436	80%	65%

Source: (Drewery Maritime Research, 2021).

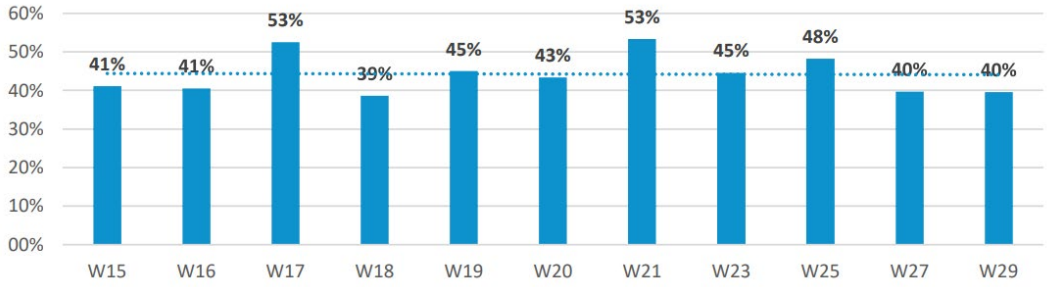

Fig. 3. Percentage of ports touched by blank sailing in 2020
Source: (UNCTAD, 2021a).

In the first half of 2020, there was a fall of 3.5 % of container ship calls in comparison with the corresponding period from the previous year. Since the declaration of the pandemic by WHO, container ship calls worldwide were 5.8 % below the level during the same period in 2019 (UNCTAD, 2021a). According to the IAPH-WPSP COVID-19 Economics Impact Barometer, at least 40 % of container ports worldwide have experienced blank sailings each week since March 2020 (Fig. 3). For example, on the Asia-United States trade route, blank sailings reached 19 % in May 2020 (which means that 47 out of 249 calls were blanked).

Blank sailings cause significant consequences in especially big container ports, such as peaks in ship-to-ship and yard-to-ship operations as well as labour disturbances due to being overworked on some days followed by several days off-duty (UNCTAD, 2021a).

The repositioning of empty containers was experiencing significant disturbances globally. As a consequence of the empty container shortage for export, prices per container underwent a sharp increase.

Another reason for the empty container crisis was their prolonged keeping hinterland. The problem was exacerbated by COVID-19 restrictions in inland transport, measures taken at the border crossing, shortages of drivers, and staff issues at intermodal terminals. Pandemic problems among importers also contributed to prolonging the return of empty containers to the system.

The blockage of the Suez Canal from 23 until 29 March 2021 by the big container ship Evergiven carrying over 18300 containers, was another pivotal factor affecting empty container management. The containers trapped on this ship but also those blocked on all the ships queuing at the entrance to the Canal and later waiting in lines in the ports to be transhipped, reduced the global fleet of available containers significantly. Ships from China or India had to sail around Africa to reach Europe. Considering that about 50 large ships pass through the Canal every day and that as much as 13 % of all global trade, including 30 % of global container traffic, passes through the Canal, the blockage had critical consequences. At that time, the cost of transporting a container has risen from USD 1 500 before the pandemic to USD 8 000–10 000 (Russon, 2021). This resulted in the price rise not only for containers on the route passing through the Suez Canal but on nearly all routes. Large rises on long routes were explained by higher employment on a weekly basis, so more containers were stocked there. Therefore, in the light of a dramatic shortage of containers, importers in this area had to pay not only for the transportation of a full container but also for the inventory cost of an empty container.

Due to the blockage, container ships and tankers were not delivering food, fuel and production components to Europe, and European goods could not have been exported to the Far East. Additional charges were introduced, such as equipment imbalances and/or congestion charges and temporary storage payments. The other consequences followed: longer handling times, increased demurrage charges and port congestions caused by hundreds of delayed ships to be served. Those delays had a severe impact on production companies. They faced a difficult dilemma: wait for their order, organise alternative transport by land or make a new order with an alternative transport route. The natural decision was to shift to rail, and this again resulted in the lack of empty containers and space available on the trains. In the case of certain types of loads or transportation corridors, this phenomenon of the modal shift (from maritime to rail transport) continues.

2. Effect on Eurasian transport

The development of container transport is also stimulated by various bilateral agreements and initiatives to expand intermodal corridors, such as China's One Belt One Road (OBOR) project. Many countries along the route connecting Asia to Europe were very interested in active participation in this initiative, expecting benefits in terms of investment, infrastructure expansion and future benefits from the development of trade and transport in the area. The OBOR idea embraces the development of land and maritime transportation corridors linking Asia and Europe.

Many of the projects under OBOR are performed in developing countries where the control of the pandemic is weak because of the slow vaccination process. Therefore, there is a significant delay in the implementation of the projects. The long-term impact of the pandemic on OBOR can be complex. There are major problems with financial viability as banks decide not to proceed with funding.

The main source of OBOR funding is the Chinese development banks, the Silk Road Fund, the New Development Bank and the Asian Infrastructure Investment Bank. Since the long-term profitability of the projects is threatened, the continuation of the financing is questionable. In China, the priority is set on the restoration from the pandemic crisis and investments in the domestic market (Wu et al. 2020).

China, as the "world's factory", is the global leader in container and bulk transport, with almost half of the global growth in maritime trade in the last decade. In 2018, China's maritime imports were estimated to be a quarter of the world's maritime trade. In this context, the outlook for this trade is highly dependent on the Chinese economy. It is difficult to foresee the extent to which the COVID-19 pandemic and the ambiguities surrounding the pandemic outbreak in China, and the circumstances of its global spread would cause reluctance to cooperate with China or to purchase Chinese products. The consequences for trade and transport in this respect can only be assessed over time.

The pandemic exposed the weakness of long supply chains and dependence on Asia. Some companies looked for more secure alternatives for their future. The OBOR partner countries focused on fighting the pandemic, limiting the spread of the virus and supporting health care, which resulted in less attention to infrastructural investments. Therefore, the development of intermodal infrastructure on the OBOR route has been hampered.

3. Measures to build-up resilience

The global impact of the COVID-19 pandemic proved beyond any doubt that measures have to be taken to improve the resilience of supply chains and, consequently, container transport. The two relevant terms referring to the situation are resilience and vulnerability. Resilience describes the capability of dynamic systems to positively react to disruptions, whereas vulnerability pertains to the capability to react negatively (Chen et al., 2018). Berle et al. (2011) and Chen et al. (2018) indicated that resilience deals with the consequences of hazards after their occurrence. Increasing a system's resilience should reduce its vulnerability. One aspect of the problem is the resilience and vulnerability of supply chains with the perspective of safe distribution and diversification of suppliers, which is the responsibility of enterprises. The other side is the resilience and vulnerability of ports and container terminals to provide smooth operation despite unexpected events.

The scale of the COVID-19 pandemic disruptions was difficult to foresee, and it brought attention to the solutions making the supply chains more reliable and resilient. Since container transport is a result of global trade, these two perspectives of entrepreneurs providing trade exchange should also be considered (Table 3).

The topic of shortening the supply chains and reducing the dependence on Chinese production returned. The UNCTAD experts indicate three areas important for the future preparation for further disruptions (UNCTAD, 2021a):

- facilitation and digitalisation of trade;
- tracking and tracing;
- competition in maritime transport.

The need to reduce the physical contact and paper documentation triggered the acceleration of digitisation solutions. In a broader sense, the value of digitalisation and even further digital transformation became clearly visible. Although tracking maritime traffic has been a vibrant field for development, much needs to be done in this respect. Providing a robust solution for empty container repositioning remains

Tab. 3. Implications affecting container transport resilience

Importers, exporters	Ports, container terminals and depots
analysis and redesign of supply chains, deglobalisation, awareness of all triers of suppliers	digitisation, digitalisation, digital transformation, limitations of personal contact and paper documentation
more attention brought to risk management	intensified efforts to provide robust solutions for tracking and tracing
advancement of technology use, digitisation and digitalisation	automatisation, application of drones, advanced analytics, internet of things, digital twins, blockchain, virtual reality and augmented reality
higher responsibility of supply departments organising transport, high competences and market knowledge as well as flexible reaction to disruptions needed	investment in advanced tools optimising terminal operations with consideration of mega container vessels on one side and limited resources (human, equipment, yard) on the other side; resilience to big differences in peak and non-peak periods caused by disruptions such as the pandemic

a challenge due to the low transparency of the process, not including all containers in computer systems and insufficient tracking. The pandemic has shown how varied is the level of information technology used in ports. New realities forced terminals to exchange data with new stakeholders in a faster and more transparent way. Communication had to take place between the company and emergency services, local communities, the media or, to a greater extent, with employees. The information about infections, changes in terminal operations, delays, congestion, etc., has to be distributed on time. An important aspect of this process is also to educate employees about changed working rules, restrictions, sanitary rigour or procedures related to the detection of infection. This challenge is particularly demanding for operators with a low level of digitalisation. In this light, even greater importance is placed on the recommendation of Szymczak et al. (2018) on data integration implementation within the information structure of the whole supply chain.

Many local hubs, especially in developing countries, have often failed to keep up with the achievements of modern technology. Only 49 of the 174 Member States of the International Maritime Organization have fully functioning Port Community Systems, which are considered the cornerstone of any port in the current digitalised business (World Ports Sustainability Programme, 2020). They rely on the physical exchange of documents between ships, land carriers and the port. This exposes employees to infections. It also raises an additional problem. The low level of digitisation means that a company has less potential to reorganise work to an online mode in critical periods. Realising the urgent need for digitisation, the International Association of Ports and Harbors (IAPH), BIMCO, the International Cargo Handling Coordination Association (ICHCA), the International Chamber of Shipping (ICS), the International Harbour Masters' Association (IHMA), the International Maritime Pilots Association (IMPA), the International Port Community Systems Association (IPCSA), the International Ship Suppliers' Association (ISSA), the Federation of National Associations of Ship Brokers and Agents (FONASBA) and the PROTECT Group provide a joint effort to accelerate digitisation in the port sector, especially support development in emerging technologies, such as artificial intelligence, advanced analytics, internet of things, digital twins, robotics process automation, autonomous systems, blockchain, virtual reality and augmented reality.

Automatisation of operations in big container terminals with few staff members proved to increase resilience and maintain the terminal's undisturbed functioning during the pandemic due to little required personal contact. Automatisation provides the physical flow of containers in the terminal by means of automatic cranes and automatic guided vehicles (AGV), as well as assures real-time data transmission. Technologies allow real-time decision-making based on both current and historical data. This helps synchronise all elements of the terminal operation and reduces the reaction time needed to make decisions. Another interesting aspect of automatisation is the use of aerial vehicles (UAVs) or

aerial drones, limiting human interaction and reducing the exposure of people to risks (Otto et al., 2018). In container terminals, drones are already used for inspections of cranes, yards, work safety and container security.

An inspiring example of using drones for transportation is presented by Wang et al. (2022). In this paper, the problem is modelled as the Piggyback Transportation Problem, where an autonomous driving vehicle carries drones or delivery robots. This study refers to Amazon's last-mile concept and the flying warehouse, which launches drones, and upon their return to an earthbound depot, they are resupplied to the flying warehouse by an air shuttle. This solution could also be applied for autonomous or non-autonomous ships or vehicles from where drones carrying containers are distributed to difficult-to-reach or pandemic-affected places. It allows for the distribution without berthing to the port. Drones carrying containers have already been tested by the port of Hamburg (HHLA, 2021). Hamburger Hafen und Logistik AG (HHLA) can be perceived as a leader in drone application in the field, providing advanced software and a drone control centre.

The shortage in containers and ship supply capacity is attributed mainly to the disruptions caused by the pandemic, but it should be observed that national competition authorities should monitor freight rates and market behaviour (UNCTAD, 2021a). Policymakers should strengthen national competition control authorities in the area of maritime transport and ensure that they provide the necessary regulatory oversight.

The pandemic proved that diversification of supply chains to a broader array of locations and not limited to one source or one region provides safety and resilience. Moreover, transparency of a supply chain should be ensured to make companies aware of where their supplies of all tiers are located. While

corporations know who they directly purchase from (their tier 1 suppliers), they often can lack transparency about their second- and third-tier suppliers and beyond (Cybersecurity and Infrastructure Security Agency, 2020). Long and complex supply chains, e.g., the dependency on Chinese suppliers, have proved to be risky. The delays caused by the pandemic as well as the Suez Canal blockage brought attention to a higher responsibility of supply departments organising transport. It was their task to maintain production at their enterprises unstopped, which caused a big pressure on staff members. It proved how high competences, market knowledge and flexible reaction to disruptions are needed to provide supplies on time in such critical situations.

Conclusions

The pandemic brought changes in transport mobility patterns, reversing some trends (Kuźmicz et al., 2022; Kiryluk et al., 2021). The indirect effects of the pandemic, including the reduced availability of transport, showed how quickly nature restored when humans stopped for a moment, proving that sustainability is not just a buzzword but a necessity. In this sense, paradoxically, the pandemic also had some positive impacts. One such example is the influence on the environment. According to Rothengatter et al. (2021), the CO2 emissions were reduced worldwide by 6.3% in 2020 compared with 2019. They indicated that the transport sector was responsible for about 25 % of emissions and that the strict lockdown measures contributed to the reduction of CO2 emissions, particularly, in the first quarter of 2020, due to a reduction in the overall traffic activity.

Čurović et al. (2021) performed a time comparative analysis of shipping traffic, meteorological conditions, and noise emissions from the port. The number of ships decreased in the analysed period by 35 %, and the noise levels during the night decreased by 2.2 dB to 5.7 dB. The results showed that moored ships and industrial activities were the most dominant source of noise and should, therefore, be regulated internationally.

However, the study results by Liu et al. (2021) showed that the ship emissions in ports increased by an average of 79 % because of the prolonged turnaround time in port. It is important that most ship emissions occurred during the extended staying time at berth and anchorage areas due to longer operational times caused by the pandemic. According to the investigation, the increases ranged from 27 to 123 % in the total emissions across ports, with container ships and dry bulk carriers reaching the highest pollutants, increasing by an average of 94–142 % compared with 2019.

Such observations made during the pandemic should lead to constructive changes for the future, and efforts should be made to enhance solutions to protect the environment and provide resilience to the business. The research of Ketudat and Jeenanunta (2021) pointed to key factors that resulted in the

resilience of logistics during the pandemic: flexibility, a business continuity plan, diversified market, IT systems, and leadership.

The developing megatrend of deglobalisation in response to the pandemic and shortening supply chains may influence container transport. The throughput of container terminals of ports, huge container vessels carrying over 23000 TEU and condensed traffic accumulating all kinds of delays due to the pandemic unearthed issues in urgent need of efficiency increase. Since port space is scarce in most parts of the world, the field is open for smart management using scientific achievements to optimise processes, improve forecasting and optimally schedule resources (Kuźmicz & Pesch, 2019; Tekil et al., 2022).

The pandemic appeared to be a strong signal (Ejdys, 2017) that such events would repeat. The COVID-19 pandemic comes in waves, and currently, high infection rates in China applying the zero-tolerance policy for COVID-19 result in big delays in factories and ports. This shows that measures have to be taken to provide a fast response to repeatable disruptions. Experts predict future pandemics and natural disasters resulting from climate change, which should motivate managers to be prepared for a new reality of transport and supply chain management. The war in Ukraine since February 2022 also proved that measures preventing disruptions in transport are pivotal. This paper thoroughly investigated the pandemic impact on container transport and offered recommendations for strengthening the resilience from two perspectives: (1) importers and exporters and (2) container terminals and depots. The key outcomes for entrepreneurs point to the analysis and redesign of supply chains towards deglobalisation, increasing awareness of all triers of suppliers, focusing on risk and disruption management supported by high advancement of technology solutions, digitisation, digitalisation (for increased effectiveness and the reduction of physical contact between employees) and higher responsibility and flexibility for departments responsible for the supply chain management. The port and terminals should increase efforts for digitisation and digitalisation, automatisation, and use of drones, and intensify efforts in providing robust solutions for tracking and tracing. Unavoidable is an investment in advanced tools optimising terminal operations considering mega container vessels on one side and limited resources on the other. A managerial insight points to the resilience in work organisation and big differences in peak and non-peak periods caused by disruptions, such as the pandemic.

Future research should embrace the development of models and algorithms providing robust solutions concerning processes in ports, container terminals and depots, resilient to big differences in numbers of containers processed in periods of accumulated work and those times with limited flows caused by delays, congestions and disruptions in transportation. Redesign of supply chains towards deglobalisation is another important direction of research, which is likely to become an intensive field of scientific investigation and practical development.

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Methods of multi-criteria analysis in technology selection and technology assessment: a systematic literature review

Justyna Kozłowska

ABSTRACT

Technology assessment and selection problems have gained importance in recent decades as the used technology often determines the enterprises' competitive advantage. Due to the extensive catalogue of criteria that should be considered and, on the other hand, the extensive catalogue of available technologies and solutions, the decision-making process of choosing a technology becomes a significant challenge for organisations and individuals. This study aims to identify the main research directions and trends in the scientific literature on applying multi-criteria analysis (MCA) in the context of technology assessment and/or technology selection. The author conducted a bibliometric analysis of publications indexed in the Web of Science and Scopus databases. The methodology of this study also included identifying the most productive authors, countries, organisations, and journals and analysing the occurrence and co-occurrence of terms. Final analyses included 380 publications retrieved from the Scopus database and 311 documents retrieved from the Web of Science repository. The analysis of the occurrence of terms and keywords allowed distinguishing two main research directions in using MCA methods in assessing and selecting industrial and health and medicine-related technologies. Some sub-areas have also been distinguished within these two areas: energy and renewable energy technologies, waste management, biomedical and medical technologies, and drug production technologies.

KEY WORDS

technology selection, technology assessment, multi-criteria analysis, bibliometric analysis

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Introduction

Considering the rapid technology development and its growing impact on the company's competitiveness and performance, selecting an appropriate technology that meets all requirements constitutes a challenging strategic decision problem faced by entrepreneurs and institutions (Kafuku et al., 2019). Assessing or selecting new technologies requires solving conflicts between various competing objectives to pursue environmental quality, economic

Kozłowska, J. (2022). Methods of multi-criteria analysis in technology selection and technology assessment: a systematic literature review. *Engineering Management in Production and Services, 14*(2), 116-137. doi: 10.2478/emj-2022-0021

prosperity, technological efficiency, and social equity. Such a task becomes difficult for decision makers. The research field of technology selection (TS) has been rapidly developing over the last few years (Halicka, 2020). It is strictly connected with technology assessment (TA) which allows evaluating alternative technologies in terms of economic potential, innovation level, usability, or environmental impact. Each technology has several characteristics that may be considered its advantages or disadvantages and, thus, many different factors influence the technology selection process (Hamzeh & Xun, 2019). A decision maker, either a company, an organisation, or an individual, presents certain needs and preferences. Technology selection does not rely only on internal factors of the organisation but also considers external factors. Sometimes, the most effective criteria for technology selection are not merely financial, and some other factors, such as political issues or the technology impacts on employment, are also significant (Elahi et al., 2011). Therefore, the final criteria catalogue for technology selection may consist of diverse economic, technological, environmental, and social criteria, representing such aspects as trends, functionality, flexibility, or sustainability. Furthermore, they may be described in qualitative, quantitative, or mixed categories making technology selection a complex multi-criteria problem (Saen, 2006). The technology selection problem is focused on choice (choosing the best option) or ordering (ranking) variants in the descending order of preference. Thus, it may be supported by the methods of multi-criteria analysis (MCA) or methods supporting Multi-Criteria Decision Making (MCDM) (Fang et al., 2020). These methods enable the identification of the problem, formulation of goals, analysis of the alternatives, and generation of information facilitating the final choice. MCA provides procedures, tools, and mathematical and IT methods that allow solving complex decision-making problems, the analysis of which requires considering many and, often, opposing points of view.

Recently, many articles were published addressing the above-described problems. For example, a problem of assessing green technologies with Multi-Criteria Decision Making (Si et al., 2016), TS problem in the automotive industry (Ansari et al., 2016), TS for photovoltaic cells (Fang et al., 2020), evaluation of water supply alternatives with multi-criteria decision-making methods (Savun et al., 2020), renewable energy source technology selection (Long et al., 2021) or the selection of waste-to-energy-based-distributed generation (Alao et al., 2022). A review of several sample studies has led the article's author to conclude that the topic is evolving and is worth exploring. Therefore, this study aims to answer the following research questions:

RQ1: What are the main research directions in applying multi-criteria analysis methods in the field of technology selection and technology assessment?

RQ2: Which countries, authors, institutions, and journals are most productive in this research field?

RQ3: Which multi-criteria analysis (MCA) methods are mostly used in the technology assessment and selection problems?

The study's methodology includes a systematic literature review focused on applying multi-criteria analysis in decision-making processes concerning technology selection and technology assessment. A bibliometric analysis was conducted using tools available in chosen databases to indicate the most productive authors, countries, organisations, and journals (RQ2). Furthermore, text mining analysis and visualisation techniques were used to answer the research questions RQ1 and RQ3. The methodology of the study is presented in detail in Section 2.

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1. Literature review

Technology assessment (TA) is a rapidly evolving research field visible in a growing number of research and publications appearing during the last decades (Halicka, 2020). It was primarily strictly connected with the policy tools supporting policymakers in identifying technological changes and planning future development (Delvenne & Rosskamp, 2021). So, it mainly played a crucial role in technology policy. Over time, it has evolved from a strategic government instrument to an element of business decision-making (Halicka, 2020). Nowadays, technology assessment is used at the organisational level in enterprises and institutions. It aims to reduce the human-inflicted costs of test-and-error learning in people handling new technologies and foresee the potential effects of its application on people, organisations, and the environment. The significance of the problem and its interdisciplinarity is reflected in the development of various approaches, methods, and tools for technology assessment (Chodakowska & Nazarko, 2020b). Many stakeholders and many assessment aspects must be considered in analysing and assessing technology. The criteria that are finally considered are related to the assessment context and are implied by

the subject and field of analysis (Chodakowska & Nazarko, 2020a). Technology assessment is an integral part of the technology selection process, which, in turn, focuses on choice (choosing the best option) or ordering (ranking) variants in the descending order of preference. A technology selection (TS) problem is described as identifying the best technology from a set of possible alternatives or options (Singh & Sushil, 1990). Knowing how to solve this problem will help organisations create more competitive offers and solutions and more efficient processes (Hamzeh & Xu, 2019). However, this problem usually appears complex as it encompasses the need to consider such aspects as uncertainties of technical and commercial success, current life-cycle level of the technology, possibilities of its development, environmental impact, etc. and also interactions with the current technologies in the organisation (Houseman et al., 2004; Krishnan & Bhattacharya, 2002; Wang et al., 2014). Technology selection aims "to obtain new know-how, components, and systems which will help the company to make more competitive products and services, more effective processes, and/or create completely new solutions" (Houseman et al., 2004, p. 2). The criteria affecting the technology assessment and selection may be tangible and intangible. Moreover, they might be described as qualitative or quantitative categories and may represent very different aspects of technology, including economic, social, technological or technical, and environmental (Ragavan & Punniyamoorthy, 2003; Muerza et al., 2014; Shen et al., 2010). A catalogue of final criteria is highly dependent on many conditions, like the type of technology, the goal of technology selection, the scale of the selection problem, the sector of the economy it considers, the level of governance, and the complexity of related know-how, etc. Thus, the assessment and selection of technology constitute a complex and multi-criteria problem.

Methods of Multi-Criteria Analysis (MCA) or tools supporting the Multi-Criteria Decision-Making process (MCDM) have been developing in the frame of operations research or mathematical modelling of complex decision problems. In multi-criteria analysis, no ideal or optimal solution can be found. It is a rather compromised solution that matches the decision maker's preferences in the best possible way. One of the most popular multi-criteria decision-making tools is the analytic hierarchy process (AHP), which was proposed and developed by Saaty. It enables the decomposition of a complex decision problem and the creation of a final ranking for a finite set of variants (Saaty, 1980). The method is still being developed and modified (Saaty, 2005). Other most used are SAW, TOPSIS, VIKOR, ELECTRE, and PROMETHEE. Until now, the Simple Additive Weighting (SAW) method is the best known and most frequently used discrete multi-criteria method. Its advantages are simplicity and intuitiveness in modelling the decision maker's preferences through an additive linear function (Tzeng & Huang, 2011). Both VIKOR and TOPSIS methods are based on an aggregating function describing closeness to the ideal solution. The VIKOR method ranks alternatives and determines the solution closest to the ideal solution. The base in the TOPSIS method are two "reference" points called "ideal solution" and "negative-ideal solution". The aggregate index allows for choosing the alternative that is at the "shortest distance" from the ideal solution and the "farthest distance" from the "negative-ideal" solution (Opricovic & Tzeng, 2004). The group of ELECTRE methods is based on the rule of pairwise comparisons. The method employs the concordance and discordance of the criteria and the threshold values to evaluate the scoring schemes between the available alternatives (Effatpanah et al., 2022). PROMETHEE belongs to the family of multi-criteria outranking methods based on the dominance relationship principles and a generalisation of the criterion notion (Brans et al., 1984). More knowledge on multi-criteria methods is available from outputs by Hwang & Yoon (1981), Zanakis et al. (1998), Tzeng & Huang (2011), Arslan (2017) and others.

Some studies review and examine the use of MCA methods or MCDM tools in fields of engineering and management (Mardani et al., 2018), business analytics (Yalcin et al., 2022) or financial decisions (Hallerbach & Spronk, 2003), energy planning (Pohekar & Ramachandran, 2004), the assessment of multi-sector interactions in the emerging offshore Blue Economy (Turschwell et al., 2022), geographical information systems (Carver, 1991), decommissioning of offshore oil and gas facilities (Li & Hu, 2022) or research planning (Loo et al., 1990). This study focuses on a review of the use of multi-criteria analysis methods for technology assessment and selection.

2. Research methods

A systematic literature review and bibliometric analysis are the most popular approaches in scientific research for uncovering emerging trends and identifying authors and institutions most engaged in certain

scientific fields or journals that affect the analysed subject the most (Donthu et al., 2021). Many researchers indicate main research directions or areas based on systematic literature review results (in chosen scope) (Glińska & Siemieniako, 2018; Hamzeh & Xun, 2019; Alcácer et al., 2019; Szum, 2021), research gaps (Hajduk, 2017; Winkowska et al., 2019; Szpilko et al., 2020; Ciani et al., 2022; Michalski et al., 2022) or opportunities and directions for further research (Halicka, 2017; Siemieniako et al., 2021; Belezas & Daniel, 2022; Sun et al., 2022). Many useful tools and software were developed (e.g., Gephi or VOSviewer) to analyse a set of database records resulting from searching the scientific repositories. Such software is designed to present the relationships between terms and individual elements (Gudanowska, 2017; Siderska & Jadaa, 2018). Visualisation and clustering of these relationships enable the understanding of how the research field manifests itself and develops over time. Combining results of bibliometric analysis and visualisation techniques is considered a complementary approach to studies aimed at literature review analysis and synthesis (Donthu et al., 2021). Therefore, it has been applied in this study. Considering the convergence of the research questions raised in some papers (Szum, 2021; Szpilko & Ejdys, 2022), an analogous research methodology was adopted in this study.

This study's methodology (Fig. 1) included five main stages: database selection (Stage 1), keyword selection (Stage 2), inclusion criteria selection (Stage 3), data extraction and removal of duplicates (Stage

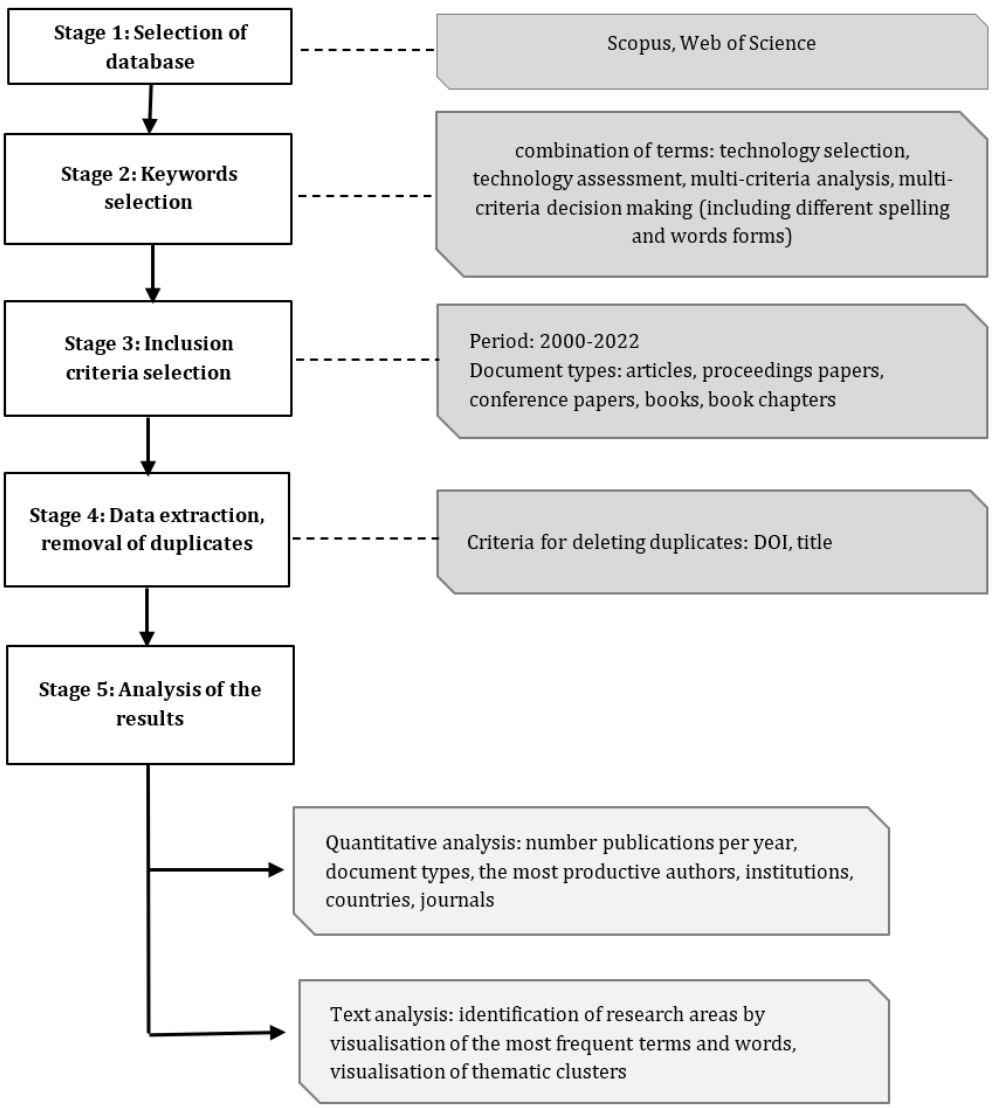

Fig. 1. Methodology of the study

Tab. 1. Search results

Step	Scopus	Web of Science
searching query	TITLE-ABS-KEY („MULTI-CRITERIA DECISION MAKING" AND „TECHNOLOG* ASSES*") OR TITLE-ABS-KEY (MCDM AND „TECHNOLOG* SELECT*") OR TITLE-ABS-KEY (MCDM AND „TECHNOLOG* ASSESS*") OR TITLE-ABS-KEY („MULTI-CRITERIA DECISION MAKING" AND „TECHNOLOG* SELECT**") OR TITLE-ABS-KEY („TECHNOLOG* ASSES*" AND „MULTI CRITERIA") OR TITLE-ABS-KEY („TECHNOLOG* SELECT*" AND „MULTI CRITERIA") OR TITLE-ABS-KEY (MCA AND „TECHNOLOG* ASSES*") OR TITLE-ABS-KEY (MCA AND „TECHNOLOG* SELECT*")	ALL=(((„TECHNOLOG* ASSES*" AND („MULTI-CRITERIA" OR „MULTI CRITERIA")) OR („TECHNOLOG* SELECT*" AND („MULTI-CRITERIA" OR „MULTI ARTERIA")) OR (MCA AND („TECHNOLOG* SELECT*" OR „TECHNOLOG*ASSES*")) OR („MULTI-CRITERIA DECISION MAKING" AND „TECHNOLOGY ASSES*") OR („MULTI-CRITERIA DECISION MAKING" AND „TECHNOLOGY SELECT*") OR (MCDM AND („TECHNOLOGY SELECT*" OR „TECHNOLOGY ASSES*"))))
Number of articles before inclusion criteria	392	321
Number of articles after inclusion criteria and removal of duplicates	380	311

4), and analysis of the results (Stage 5). The last stage of the methodology consisted of two steps: quantitative analysis of obtained results (in terms of the number of publications per year, document types, most productive authors, institutions, countries, and journals) and qualitative analysis based on text mining techniques aimed at identification of most frequently explored areas of research. The first stage was the database selection. Scopus and Web of Science were chosen mainly due to the author's free access to these repositories. However, both databases are popular in bibliometric studies, and their content is relatively wide, both in the scope of scientific thematic and in the number of publications indexed. Therefore, they appeared representative in terms of bibliometric analysis results. Database searches were performed using the following keywords in various forms and configurations: technology selection, technology assessment, multi-criteria analysis, and multi-criteria decision making. Thus, a set of publications obtained as a query phrase result was exactly and closely related to the analysed scientific field. In the next stage, the set was limited in terms of publication date (period: 2000–2022) and document types (articles and conference papers or proceedings, books, and book chapters). The search result is shown in Table 1. The search was performed in early 2022. As both databases are updated daily, a perfect replication of the search results may not be possible.

A detailed query formulated in each database is shown in the first row of Table 1. After including the selection criteria and removing duplicates, a set of 380 papers was used for further analyses from the Scopus database. A set of 311 papers was extracted from the Web of Science database. These sets were used to show the publication trends over the years and identify the most productive authors, institutions, countries, and journals. Finally, a text analysis was performed to visualise the most frequently occurring terms and words. This allowed identifying thematic clusters, which indicated the main research directions in applying and adapting multi-criteria analysis for technology selection and assessment.

3. Research results

The last 20 years of applying multi-criteria analysis to technology selection and assessment problems show a growing trend in the number of published papers (Fig. 2). The most significant increase may be noticed after 2010 — from only 5–10 in 2010 to almost 40–50 in 2021.

The publication increase index illustrates the dynamic of increase. It can be calculated as the ratio of the number of publications in a given year to the number of publications in the previous year or as a ratio to the one basic year. Considering the last ten years (from 2012 to 2021), there is a substantial dynamic visible in the growth of the number of publications in the analysed research field. Growth may be seen almost every year (columns A and B, Table 2, the value of the index greater than 1 indicates growth), and during the last ten years, the number of publica-

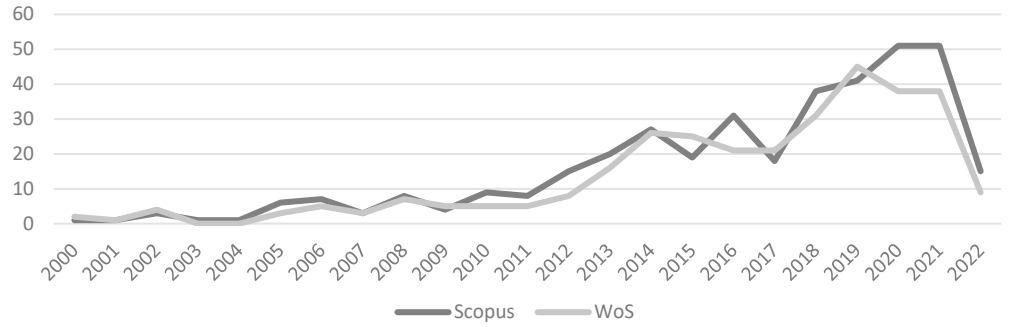

Fig. 2. Number of publications per year

tions increased six to seven times in relation to 2011 (columns C and D, Table 2). It shows rising interest in this research field, particularly in recent years, so the subject of applying multi-criteria analysis for technology assessment and/or technology selections appears to be an emerging research field. This is also confirmed by the structure of the analysed set of extracted documents in terms of type (Fig. 3). Most of them are articles (65 % among Scopus results, 76 % in WoS results) and conference proceedings or conference materials (23 % and 16 %, respectively). Few books have been published so far, typical of emerging research fields.

In the Web of Science database, each document is described with the Web of Science Category, which represents the main addressed research field. The largest part of examined documents (almost 15 %) was assigned to the Health Care Science Services category. The next three groups, almost equal in size (about 12–12.5 % of analysed documents), constitute papers classified as Environmental Sciences, Green Sustainable Science Technology, and Energy Fuel. About 11 % of publications were related to Health Policy Services and over 10 % to Operations Research Management Science. In the Scopus database, documents are assigned to the subject area. Within extracted documents, the subject area of almost 20 % was classified as Engineering, 12 % as Medicine, 11.5 % as Computer Science, 10.5 % as Business, Management and Accounting, 10 % as Environmental Studies, and over 8 % as Energy.

The summary presenting the most productive authors, countries, organisations, and journals is revealed in Table 3. The average citation count was calculated specifically for the search results using both databases' tools. For example, 57 publications in Scopus came from the USA, and their total citation number was 946, giving 16.6 citations per paper on average. The most productive authors (eight publications) in the field of multi-criteria analysis methods applied for technology selection or assessment are Büyüközkan Gulcin, a researcher from Galatasaray University (the most productive institution) in Turkey (second most productive country) and Streimik-

Tab. 2. Indexes illustrating the increase of publications in the last ten years

Year	Index of increase in the number of publications (previous year=100)		Index of increase in the number of publications (2011 year=100)	
	Scopus (A)	WoS (B)	Scopus (C)	WoS (D)
2012	1.9	1.6	1.9	1.6
2013	1.3	2.0	2.5	3.2
2014	1.4	1.6	3.4	5.2
2015	0.7	1.0	2.4	5.0
2016	1.6	0.8	3.9	4.2
2017	0.6	1.0	2.3	4.2
2018	2.1	1.5	4.8	6.2
2019	1.1	1.5	5.1	9.0
2020	1.2	0.8	6.4	7.6
2021	1.0	1.0	6.4	7.6

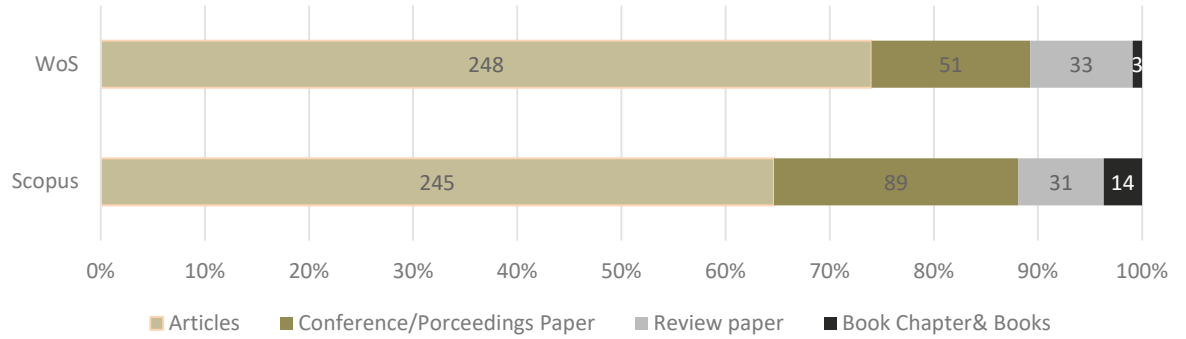

Fig. 3. The structure of search results in terms of document types

iene Dalia from the Lithuanian Energy Institute in Kaunas, Lithuania. It should be noted that Streimikiene's average citation rate is much higher than Büyüközkan's. The articles co-authored by Büyüközkan with the highest citation rate are (1) "Cloud computing technology selection based on interval-valued intuitionistic fuzzy MCDM methods" from 2018, with 46 citations in the Scopus database, and (2) "Selection of sustainable urban transportation alternatives using an integrated intuitionistic fuzzy Choquet integral approach" from 2018, with 45 citations in the Web of Science database. The most cited paper co-authored by Streimikiene is "Intuitionistic fuzzy MULTIMOORA approach for multi-criteria assessment of the energy storage technologies" from 2019, with 92 citations in Scopus and 83 citations in Web of Science.

The other authors with a similar or slightly smaller number of publications were Göçer Fethullah (Kahramanmaras Sutcu Imam University, Turkey), Kahraman Ceng (Istanbul Technical UniversityTurkey), Kalo Zoltan (Eotvos Lorand University, Budapest, Hungary), and Oztaysi Basar (Istanbul Technical University, Turkey). But the author with the highest average citation rate is Oztaysi (50.5 in Scopus and 46.8 in WoS). The countries with the highest number of publications are the United States of America, Turkey, and the United Kingdom. It should be noted that publications from the United Kingdom are the most highly cited (Scopus: 27.9, WoS: 37.6).

Among the most productive organisations are Galatasaray University, Islamic Azad University, Istanbul Technical University, University of Tehran, University of Twente, and Warsaw University of Technology. The most cited are studies from the University of Twente, Netherlands (the average citation rate of 35 in Scopus and 26.9 in WoS).

Among the top ten most productive journals, the International Journal of Technology Assessment in Health Care ranked first (12 publications in Scopus, 15 in WoS). This was followed by the Journal of Cleaner Production with 14 publications in Scopus and 12 in WoS and the International Journal of Production Research with 9 and 11 publications, respectively. However, the journal Energy, published by Elsevier, achieved the highest average number of citations in each database (Scopus: 96.8, WoS: 84.8). In comparison with other journals in the ranking, it had by far the highest average number of citations in Scopus and Web of Science databases.

The total number of citations of publications on multi-criteria analysis or multi-criteria decision making in the context of technology selection or technology assessment was 6002 for Web of Science and 6140 for Scopus. The top ten publications included two articles published in Energy (Elsevier). The most cited publication (Scopus: 264, WoS: 228) was the article by Afgan and Carvalho (2002) entitled "Multi-criteria assessment of new and renewable energy power plants". Next in the ranking list was the article "R&D project evaluation: An integrated DEA and balanced scorecard approach" by Eilat, Golany and Shtub (2008), which has 212 citations in Scopus and 160 in WoS, and "Evaluation methodologies for technology selection" by Chan, Chan and Tang (2000) which was cited 159 times in Scopus and 132 in WoS (Table 4).

Search results were analysed in the next step with different text analysis tools. The author first conducted several analyses to reveal the main research directions in the field of MCA methods applied for TA and TS, the files with the results obtained from both databases were explored separately, and maps of the frequency of terms were produced. Then, the results were merged, and a keyword co-occurrence

Tab. 3. Most productive authors, countries, organisations and journals

NO.	ITEM	NUMBER OF PUBLICATIONS		AVERAGE CITATION COUNT	
		SCOPUS	WOS	SCOPUS	WOS
AUTHORS					
1.	Büyüközkan, G.	8	8	8.9	11.9
2.	Streimikiene, D.	7	8	43.1	37.0
3.	Göçer, F.	5	6	14.8	15.2
4.	Kahraman, C.	8	6	23.25	36.7
5.	Kalo, Z.	4	6	6.3	2.3
6.	Oztaysi, B.	6	6	50.5	46.8
7.	Ijzerman, M. J.	4	5	46.0	34.6
8.	Farshidi, S.	5	3	10.4	10.7
9.	Jansen, S.	5	3	10.4	10.7
10.	Marsh, K.	3	4	20.7	46.5
COUNTRIES					
1.	USA	57	43	16.6	21.4
2.	Turkey	45	39	12.8	23.1
3.	United Kingdom	32	24	27.9	37.6
4.	Germany	30	23	19.1	21.2
5.	China	28	27	17.9	26.0
6.	Iran	28	24	11.5	10.8
7.	Italy	27	21	17.4	20.3
8.	Netherlands	25	25	23.7	21.4
9.	Canada	21	19	27.2	30.9
10.	India	18	16	17.5	17.8
ORGANISATIONS					
1.	Galatasaray University	15	13	15.6	20.9
2.	Islamic Azad University	5	10	20.6	18.9
3.	Istanbul Technical University	15	10	25.4	30.8
4.	University of Tehran	8	7	14.6	14.0
5.	University of Twente	7	7	35.0	26.9
6.	Warsaw University of Technology	8	7	8.5	6.5
JOURNALS					
1.	International Journal of Technology Assessment in Health Care	12	15	31.8	23.9
2.	Journal of Cleaner Production	14	12	21.1	20.5
3.	International Journal of Production Research	9	10	29.6	27
4.	Cost Effectiveness and Resource Allocation	9	5	11.0	4.8
5.	Expert Review of Pharmacoeconomics and Outcomes Research	5	7	12.0	15.0
6.	Sustainability	8	6	8.6	6.5
7.	Energies	6	6	15.0	14.2
8.	Energy	6	6	96.8	84.8
9.	Expert Systems with Applications	5	5	32.2	27.6
10.	Renewable and Sustainable Energy Reviews	5	5	41.6	35.0

Tab. 4. Most cited publications

No.	Author(s), year	Title	Source	Citation count	
				Scopus	WoS
1.	(Afgan & Carvalho, 2002)	Multi-criteria assessment of new and renewable energy power plants	Energy 27(8), pp. 739–755	264	228
2.	(Eilat et al., 2008)	R&D project evaluation: An integrated DEA and balanced scorecard approach	Omega-International Journal of Management Science 36 (5), pp. 895–912	212	160
3.	(Chan et al., 2000)	Evaluation methodologies for technology selection	Journal of Materials Processing Technology 107 (1-3), pp. 330–337	159	132
4.	(Marsh, K. et al., 2014)	Assessing the Value of Healthcare Interventions Using Multi-Criteria Decision Analysis: A Review of the Literature	Pharmacoeconomics 32 (4), pp. 345–365	155	140
5.	(Oztaysi, 2014)	A decision model for information technology selection using AHP integrated TOPSIS-Grey: The case of content management systems	Knowledge-Based Systems 70, pp. 44–54	132	113
6.	(Scott et al., 2012)	A review of multi-criteria decision-making methods for bioenergy systems	Energy 42(1), pp. 146–156	132	116
7.	(Choudhury et al., 2006)	Consensus-based intelligent group decision-making model for the selection of advanced technology	Decision Support Systems 42(3), pp. 1776–1799	131	107
8.	(Si et al., 2016)	Assessment of building-integrated green technologies: A review and case study on applications of Multi-Criteria Decision Making (MCDM) method	Sustainable Cities and Society 27, pp. 106–115	123	115
9.	(Xiao, 2018)	A novel multi-criteria decision making method for assessing health-care waste treatment technologies based on D numbers	Engineering Applications of Artificial Intelligence 71, pp. 216–225	122	119
10.	(Peterseim et al., 2013)	Concentrated solar power hybrid plants, which technologies are best suited for hybridisation?	Renewable Energy 57, pp. 520–532	120	101
11.	(Onar et al., 2015)	Multi-expert wind energy technology selection using interval-valued intuitionistic fuzzy sets	Energy 90, pp. 274–285	114	106
12.	(Danner et al., 2011)	Integrating patients' views into health technology assessment: Analytic hierarchy process (AHP) as a method to elicit patient preferences	International Journal of Technology Assessment in Health Care 27(4), pp. 369–375	111	96
13.	(Karsak & Ahiska, 2005)	Practical common weight multi-criteria decision-making approach with an improved discriminating power for technology selection	International Journal of Production Research 43(8), pp. 1537–1554	110	102

map was generated. These three analyses led to similar conclusions and allowed identifying mostly discussed and explored research areas within the analysed topic.

The map of the most frequently occurring terms based on the text of documents extracted from the WoS database was generated with VoSViewer. Fig. 4 shows the most common words in abstracts and titles

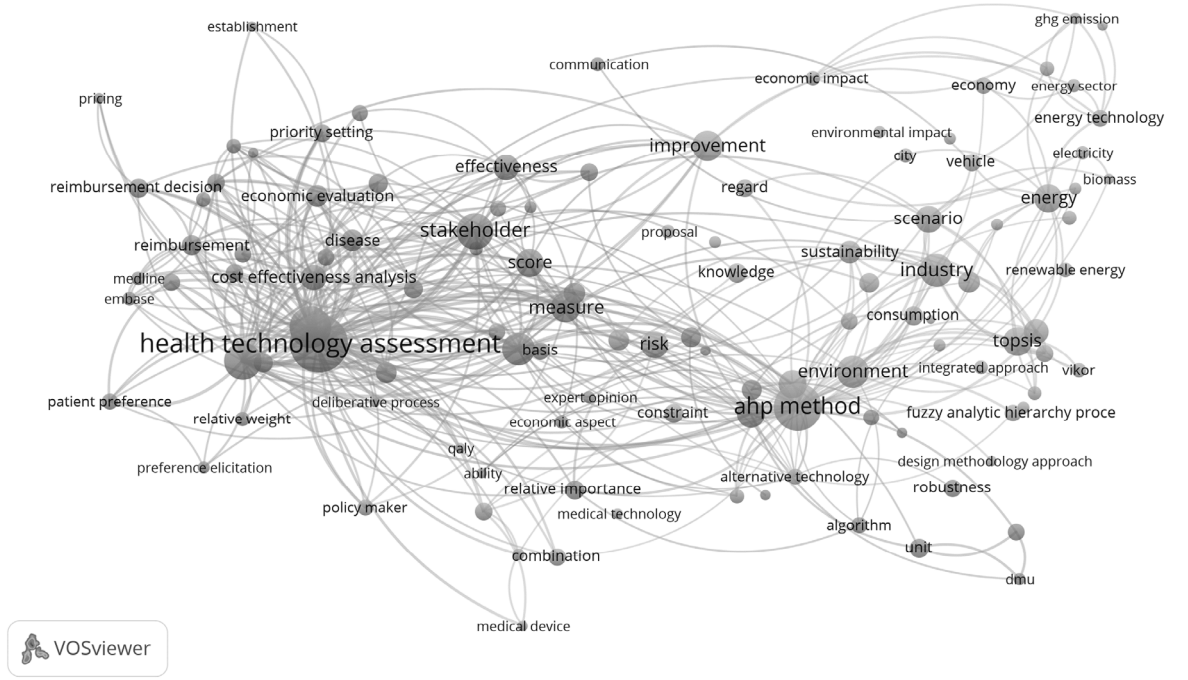

Fig. 4. Most frequent terms in documents extracted from the WoS search

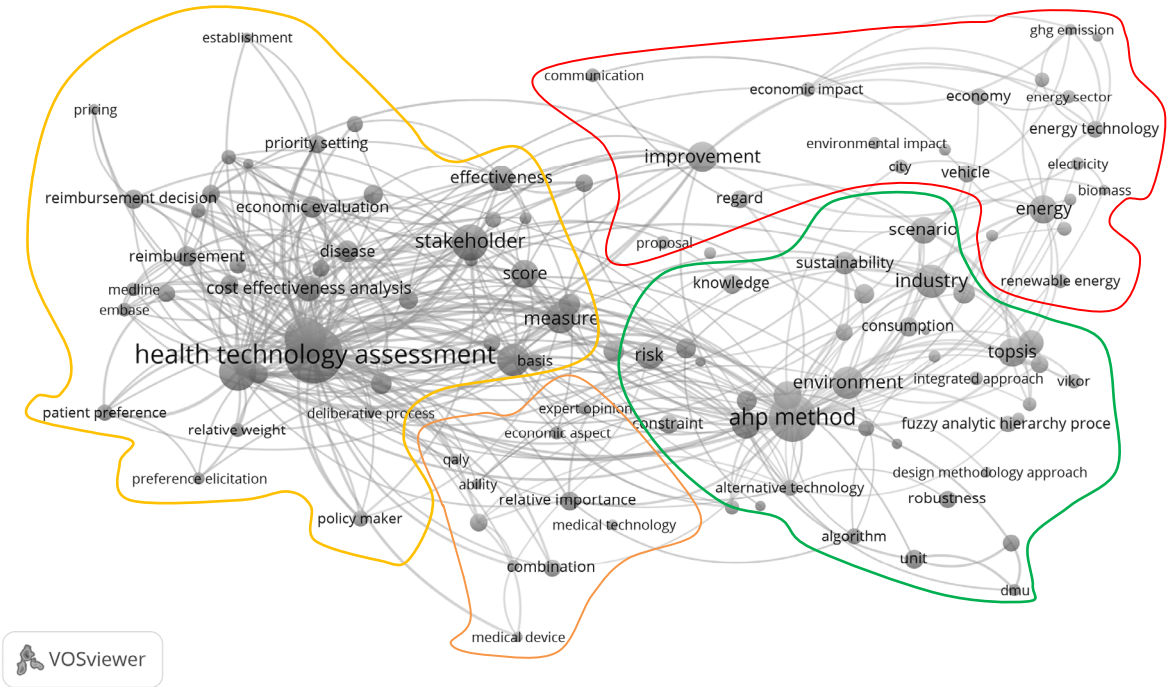

Fig. 5. Thematic clusters on MCA methods applied in technology selection or assessment

of extracted documents. To better understand the visualisations, it should be explained that the size of a caption (or circles) reflects the number of documents in which the term was found. The distance between two terms explains an estimated indication of the relatedness of the terms. The relatedness of terms was determined based on co-occurrences, so the larger the number of documents in which two terms were both found, the stronger the relationship between them (van Eck & Waltman, 2017). It may be observed that health technologies were the most popular subject of assessment and selection with the MCA methods. Also, the terms industry, energy, environment, AHP and TOPSIS are drawn in big circles, demonstrating that these topics were among the most frequently raised.

The main trends in adapting MCA methods for technology selection and assessment may be identified based on the map. The most related terms (shown by the densest network of connections) are enveloped with a yellow line in Fig. 5. These words seem to concern health and healthcare technologies in general. This area contains terms health technology assessment, disease, reimbursement decision, patient preference, effectiveness, stakeholder, and establishment or policymakers.

Terms circled by an orange line are also related to healthcare technology, but they seem to focus more on technical aspects of health technologies (medical device, medical technology), and the density of connections is lower. Words inside a green envelopment represent documents that address the use of different MCA methods for industry technologies considering environmental issues and the sustainable impact of such technologies. The area marked with a red line contains words that seem to relate to research in energy technologies, mainly in the context of its economic and environmental impacts and in the scope of improvements. Also, words like renewable energy, GHG emission, vehicle, and biomass occurred near each other, which means a frequent appearance in the same documents.

Next, the results of the search conducted in the Scopus database were processed using the Statistica software and the Wordart tool. In Statistica, the text mining techniques allow calculating the frequency of

Tab. 5. Most frequently occurring terms in documents extracted from the Scopus database

Word / Phrase	Count	Number of documents
health technology	390	90
energy	140	41
fuzzy	107	45
treatment	94	39
economic	93	63
optimization	85	8
development	84	51
environmental	70	54
systems	70	39
AHP	69	36
hierarchy	58	46
clinical	51	20
sustainability	50	26
waste	46	21
cost	44	32
social	42	32
policy	38	27
renewable	33	16
risk	32	18
sensitivity	30	23

Source: elaborated by the author using Statistica software.

word occurrence. The list of words with the highest number of occurrences is presented in Table 5.

Then, after cleaning the list and removing words that have no meaning, verbs, adverbs, etc., the word cloud was created using the Word Art tool. Table 5 gives a list of top common words. The whole list of terms generated by the Statistica text mining tool was used to create the cloud of words (Fig. 6).

Terms that appear in the word cloud seem to point to similar topics as the WoS map (Fig. 5). The word cloud shows graphically the importance (in this case, the frequency) of the terms, which may be evaluated by the size of the word. It does not, though, carry any information about the relationship between terms. Some conclusions may be drawn based on the relationship of the word size. For example, health technology is almost the same size as energy. Judging from the number in Table 5, energy issues may be much less frequently raised than health technology concerns. However, considering other terms' occurrence, in the cloud visualisation, both terms were considered equally important. Noteworthy, as far as methods are concerned, there is a particular noticeable interest in the AHP method and in using fuzzy logic. Other relatively frequently appearing words that may suggest key research directions are sustain-

Fig. 6. Word cloud representing the most frequently occurring terms regarding MCA methods applied in TS and/or TA

Source: elaborated by the author based on Scopus search results.

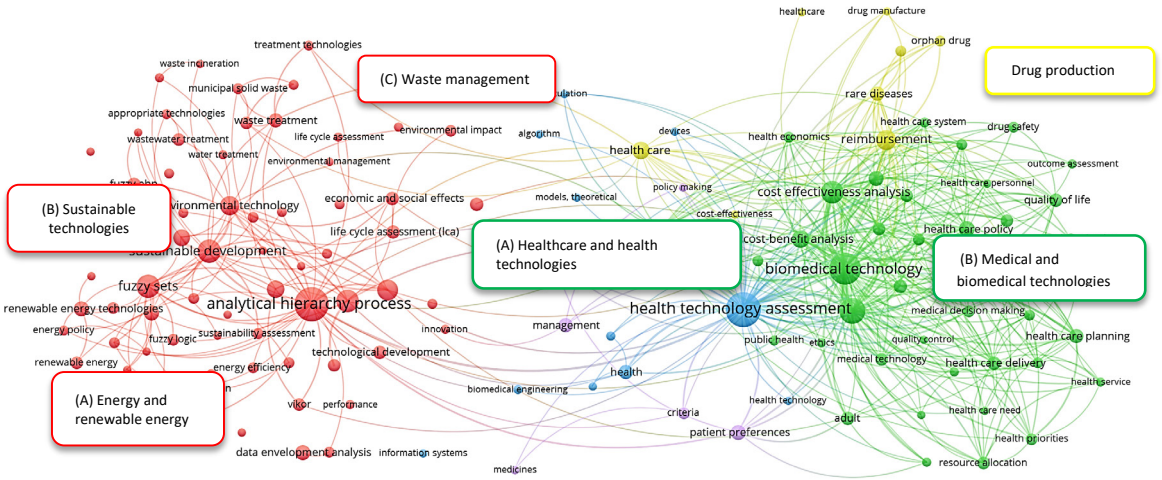

Fig. 7. Keyword co-occurrence map

Source: elaborated by the author based on merged Scopus and WoS search results.

ability/sustainable development, environmental problems, and renewable energy. In this map, new areas may be discovered, i.e., small-sized words like water, wind, wastewater, waste, supply, transport, and automotive. It provides a guideline for new kinds of topics brought into the scientists' consideration. They are relatively rarely discussed in comparison to the most popular topics, e.g., energy or healthcare technologies but may constitute an emerging research field.

The last step of text analysis was a visualisation of keyword occurrence and co-occurrence. The map was generated based on the file containing merged results from both databases. The map (Fig. 7) was created after removing general keywords (like article, questionnaire, or names of countries) and phrases used in the search query and using a thesaurus for phrases of similar or identical meaning. Clustering keywords gives more general insight into research directions in the analysed scientific field.

In this map, colours indicate associations, and the line size informs about the co-occurrence frequency (the thicker the line between terms, the more frequently they appear in one document). Research topic emerging by clustering keywords shows two main groups of the topic raised in scientific papers: industrial technology (red cluster) and healthcare/medical technologies (green cluster) assessment and/or selection. Within industrial technologies, the cluster can be divided into three subareas: (A) energy and renewable energy technologies, (B) sustainable technologies, and (C) waste management. The green cluster may be split into two themes: (A) healthcare and health technologies and (B) medical and biomedical technologies. Furthermore, one smaller cluster (yellow) can be pointed out with fewer connections and minor co-occurrence, gathering terms related to drug production.

4. Discussion of the results

The research field of technology assessment and selection with multi-criteria analysis does not seem extensive now as for this analysis, the set of publications retrieved from both databases contained around 300 documents in each set. So, it is a rather narrow field of research with a rapidly growing body of literature. Between 2012 and 2021, the number of articles and other documents published each year grew several times. In 2021, the number of publications was 6 to 7 times higher than in 2012. It demonstrates the rapidly increasing interest in the academic environment in this research field.

One of the main findings of this study is the identification of thematic clusters representing current directions of the research in the field of MCA methods applied in TA and TS problems. This is targeted toward the first research question, RQ1 "What are the main research directions in applying multi-criteria analysis methods in the field of technology selection and technology assessment?". First, it should be noted that, in general, a vast majority of the studies propose a certain MCA method, a combination of methods, a modification of methods, a few-step methodology, or more advanced solutions based on MCA methods (e.g., computer programs or decision support systems) for assessment or selection of technology of a certain type or destination. Using the MCA method allows building the ranking of alternatives and then choosing the best option. A part of the studies focuses on criteria choice and weighting, or preferences and priority setting (e.g., Kaur et al., 2019; Freire et al., 2019, Castro et al., 2018; Mobinizadeh et al., 2016; Daniels, 2018; Isoke & van Dijk, 2014; Husereau et al., 2010), namely, concentrate on adjusting the method to the particular technology, sector or problem. But primarily, it is the assessment or selection of the best alternative which is the main aim of the studies. And the key thematic groups in which the TA and TS problem-solving are supported with the MCA method are described by the clusters created based on keyword occurrence and co-occurrence.

The biggest thematic cluster considers the assessment and selection of healthcare and health technologies, within which a subarea of medical and biomedical technology selections was distinguished. Health Technology Assessment (HTA) is a well-established research field (Oortwijn & Klein, 2019). Within the search results, documents related to healthcare technologies or health constitute almost 30 % in WoS and around 14 % in Scopus. There are many developed HTA models or methodologies (Karatas et al., 2018; Improta et al., 2018; Santos & Garcia, 2010; Lasorsa et al., 2019). A considerable part of studies focuses on patient preferences (Marsh, Caro, Hamed, Zaiser, 2017; van Overbeeke et al., 2021; Mühlbacher & Juhnke, 2016; Hummel et al., 2012; Danner et al., 2011; Badia et al., 2019), or other stakeholders (hospital employees, managers, etc.) of the healthcare system (Wahlster et al., 2015; Karrer et al., 2021; Tal et al., 2019). There are also papers analysing and evaluating the application of Multi-Criteria Decision-Making (MCDM) tools in HTA (Kelley et

al., 2018; Marsh et al., 2018; DiStefano & Krubiner, 2020; Schmitz et al., 2016). As far as medical and biomedical technologies are concerned, the following technologies were the subject of assessment or selection with multi-criteria decision-making tools: medical device assessment (Nur et al., 2020; Rogalewicz & Jurickova, 2014;), selection of various medical devices and equipment (Ivlev et al., 2015; Jurickova & Kraina, 2014; Hilgerink et al., 2011; Villegas et al., 2020), including devices for individual patient use in hospitals (Martelli, 2016) or innovative sterile medical devices (Boudard et al., 2016), and also, such niche subject like an assessment of optoelectronic biosensors for oncology (Improta et al., 2019).

A smaller area, also related to this scientific field, seems to be related to drug production. This cluster had words like drug manufacture, orphan drug, drug safety, and rare disease. Various investigators have proposed orphan drugs and rare disease-specific MCA approaches by considering criteria specific to rare diseases. Often, orphan-drug technologies are assessed from the perspective of patient, public, or government preferences (Badia et al., 2019; van Overbeeke et al., 2019; Kwon et al., 2017; Laba et al., 2020; Kolasa et al., 2018). There are also several studies focusing on the review in the assessment of rare disease therapies or orphan drugs from the literature's perspective (Baran-Kooiker et al., 2018; Zelei et al., 2021) or a more practical perspective, such as the evaluation and review of case studies (Blonda et al., 2021; Baran-Kooiker et al., 2019; Farghaly et al., 2021).

The second biggest thematic cluster covers industrial technologies assessment and selection. Although there is a part of studies focused on MCA in manufacturing or technologies (Beyaz & Yildirim, 2019; Büyüközkan & Göçer, 2020; Schneberger et al., 2019), most articles may be associated with one of three distinguished subareas: (a) energy and renewable energy technologies, (b) sustainable technologies, and (c) waste management technology. Analysing search results in terms of categories (in WoS) or the subject area (Scopus), over 8 % in Scopus and around 12% in Web of Science were evidently or partly related to the energy and renewable energy technologies. The most explored subjects are technology selection of solar and photovoltaic systems (Fang et al., 2020; Dat et al., 2014; Ghasempour et al., 2019; Yimen & Dagbasi, 2019; Sellak et al., 2017; Ma et al., 2013), renewable energy storage (Liu & Du, 2020; Zhang et al., 2019; Qie et al., 2021) wind energy technologies (Onar et al., 2015; Narayanamoorthy, 2012) or hybrid renewable technology solutions (Ali et al., 2020; Peterseim et al., 2013). Within the second subarea, sustainable technologies, there are studies on choosing the best alternative industrial technology selection problems considering the sustainability perspective in general (Ibanez-Forez et al., 2014; Gilde-Castro et al., 2009; Jin & Gambatese, 2020; Ren & Lützen, 2015) or some particular issues like greenhouse gas emission (Streimikiene et al., 2013; Streimikiene & Balezentiene, 2012), transportation technologies (Štreimikiene, 2013; Oztaysi et al., 2017) or sustainable supply chain technologies (Khatri & Srivastava, 2016; Buyukozkan & Gocer, 2019). Waste management technology assessment and/or selection is another identified subarea. A substantial part of the studies concerns wastewater treatment technology selection (Ilangkumaran et al., 2013; Fetanat et al., 2021; Aydiner et al., 2016; Sadr et al., 2013; Meerholz & Brent, 2013; Salamirad et al., 2021) with the use of MCA methods. Some authors address problems of waste disposal technology selection (Jiang et al., 2015; Govind Kharat et al., 2019), biowaste treatment technology (Mpanang'ombe et al., 2018) or food waste technology (Chadderton et al., 2017). Many studies address interdisciplinary subjects, for example, sustainable waste disposal management (Torkayesh et al., 2021; Kharat et al., 2020). Consequently, industrial technology assessment and selection represent the main direction of research, covering, in particular, the three above-mentioned areas.

As far as RQ2 is concerned, namely "Which countries, authors, institutions, and journals are most productive in this research field?", a large part of the previous section contains the answer to this research question.

Regarding RQ3, "Which multi-criteria analysis (MCA) methods are mostly used in the technology assessment and selection problem?", an answer can be given by the analysis of a map that visualises the most frequently occurring words. An obvious leader in the MCA method used for TA and/or TS is the Analytical Hierarchy Process (AHP method), represented by one of the biggest circles or captions in visualisations (Fig. 4–7). Also, TOPSIS and VIKOR methods appeared on the maps. TOPSIS was proposed inter alia in the assessment of concentrated solar power technologies (Cavallaro et al., 2019), selection of sustainable urban transportation alternatives (Buyukozkan et al., 2018), healthcare waste treatment technology selection (Lu et al., 2016) or in the selection of waste-to-energy technologies for distributed

electricity generation (Alao et al., 2020). Vinodh, Nagaraj, and Girubha show that VIKOR is an appropriate technique to provide effective solutions for supplier selection, concept selection, and planning (Vinodh et al., 2015). The method was also used in the selection of healthcare waste treatment technology (Ada & Delice, 2019). Renewable energy technologies, for example, a solar photovoltaic microgrid system, have also been analysed and selected by the VIKOR method (Ighravwe & Mashao, 2019). These three methods are relatively the most frequently used for TS and TA problems.

There are also studies proposing other MCDM methods to assess or select a technology, but these studies are less common, and for that reason, they did not get on the map. For example, using PROMETHEE II was evaluated and recommended for advanced manufacturing technology selection (Kolli & Parsaei, 1992). And for less recognised problems, like selecting proper technologies for power smart grid systems, a simple SAW method was successfully used (Montazeri et al., 2017). A MULTIMOORA approach was proposed by Zhang and others for the assessment of energy storage technologies (Zhang et al., 2019). It should also be noted that authors often proposed integrated approaches combining classic MCA tools with other methods or the use of several methods in one study or problem for comparing the results. Although Data Envelopment Analysis (DEA) is not a classic multi-criteria method, it is proposed as an integrated approach to improve discrimination power for technology selection (Karsak & Ahiska, 2005). Stojanovic et al. (2015) proposed a combination of AHP, which is used to study the structure of the TS process and to determine the importance and impact of specific criteria in the selection process, and the ELECTRE method, used for creating the final ranking of alternative technologies. Other authors advised combining two or more methods of analysis that may be complementary or give comparable results. This way, Tzeng, Lin, and Opricovic (2005) first applied AHP to determine the relative weights of evaluation criteria. Then, they compared TOPSIS and VIKOR and applied them to determine the best compromise alternative fuel mode. In another study, analysing the selection of a power plant running on renewable energy sources, the authors proposed an integrated approach of complementing outcomes of SWOT analysis with PROMETHEE ranking results. The authors believed that such a combination facilitates the formulation of the basis of future renewable energy policies more objectively (Özkale et al., 2016). An interesting case of desalination technology selection was conducted by researchers from India. In this study, TOPSIS and PROMETHEE-2 were used, and both methods resulted in the same ranking pattern. However, TOPSIS gave the results quicker than PROMETHEE-2. So, in a case with most calculation data being quantitative, the authors recommended using TOPSIS over PROMETHEE-2 (Vivekh et al., 2015). Discussing the MCA methods used for technology assessment and selection, it is noteworthy that fuzzy sets or fuzzy logic are often applied to evaluate different criteria affecting the alternative technologies (Elahi et al., 2011; Onar et al., 2015; Long et al., 2021; Mall & Anbanandam, 2022). A multi-criteria analysis often involves expert opinions to assess criteria weights or to set the priorities and preferences. The problems are usually complex, making it difficult to clearly and precisely give opinions or assessments in numbers. Therefore, fuzzy sets are recommended to capture fuzzy and uncertain cognitive information (Long et al., 2021). It helps to deal with the vagueness of human thought and judgments like "approximately between $xxx and $yyy", "about $80", "very low", "medium", etc. (Chan et al., 2000).

Conclusions

This paper presented a systematic literature review focused on the identification of main directions in research relating to the use of multi-criteria analysis in the field of technology assessment and selection. Two main directions of adapting MCA methods in these decision-making processes were identified: assessing and selecting industrial technologies and health or medical-related technologies. Within industrial technologies, energy and renewable energy technologies have particular attention in academic studies. Within health and medical technologies, despite the major advantage of studies on healthcare-related technologies, biomedical and medical technologies constitute a substantial part of studies. Also, the assessment and selection of technologies for drug production seem to emerge as a separate and relatively frequently addressed issue. The identified areas of up-to-date research are the main contribution of this study from a scientific point of view. Also, authors, journals, organisations, and countries that contribute the most in this research field were indicated.

The study has obvious limitations. The main limitation is the choice of databases, which was deter-

mined by the author's free access. On the other hand, these repositories are often selected by other researchers for bibliometric analysis, so the results are comparable to the work of other authors. The second limitation is the formulation of the database query. Modifying the query slightly may produce a different result. To reduce this limitation, the author made several simulations with a slightly different configuration of the keywords in the query, and the difference in the results was 10 %–20 %, so the search results can be considered somewhat stable. Moreover, using the same query in a future study would give results that can be compared.

The results of this study raised many questions for the future research, e.g., a study could be interesting in identifying a catalogue of critical technology characteristics and crucial criteria in the technology selection process in the case of certain sectors or certain areas (e.g., for engineering technologies, renewable energy production, etc.), identifying patterns in using certain MCA methods in a particular sector, investigation of preferences of decision makers in different sectors or areas in the context of technology assessment, the evaluation of the actual usefulness of the MCA results in decision-making processes of technology selection, investigation of the application of the newest MCA methods in technology assessment and selection problems. The study suggests that many MCA methods are successfully used in the waste management field or biomedical technologies. These also seem an interesting field for future research.

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