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Their contribution to the quality of the journal INDECS' content is appreciated.

Zagreb, 30th December 2024 Josip Stepanić

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CYBERNETIC CONTEXT OF IMPLEMENTATION OF ARTIFICIAL INTELLIGENCE IN JUSTICE SYSTEMS

Vatroslav Zovko[1]

University of Zagreb, Faculty of Teacher Education
Zagreb, Croatia

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ABSTRACT

With introduction of ChatGPT in 2022. and its superfast popularity, artificial intelligence systems became omnipresent in almost all aspects of our society. Mutually agreed expectation is that the implementation of artificial intelligence will radically improve and transform our way of life with huge economic gains.

Wide scale introduction of artificial intelligence solutions in justice systems would have an impact not just in a technological aspect but also in social aspects of society. One of the possible perspectives to achieve better insight of the prospective of implementation of artificial intelligence in justice systems is that of cybernetics, which provides the theoretical framework for explaining the creation and maintenance of order in various systems.

This article gives an overview of the concepts of cybernetics, as a study of the complex system based on information flows, then explains the big data concept in the context of justice systems and implementation of artificial intelligence. Legal system is presented as a set of business rules which, together with databases, represent the foundation for development of efficient artificial intelligence systems. The theoretical framework of the justice system is explained from the cybernetics perspective with an emphasis on current regulatory trends in both the European Union and The United States.

KEY WORDS

justice system, large language models, socio-technical system, legal norms, artificial intelligence

CLASSIFICATION

JEL: K10, K40, O30

*Corresponding author, η: vatroslav.zovko@ufzg.hr, +385 (1) 6327300;
Učiteljski fakultet, Savska cesta 77, HR – 10 000 Zagreb, Croatia

INTRODUCTION

Artificial intelligence (AI) is gaining more popularity in every aspect of our lives, already beating humans in some areas such as reading comprehension, image recognition and language understanding [1]. Although AI is still not present or prevalent in justice systems around the world its introduction in justice systems is inevitable. Such inevitability is even recognized by the European union - in 2018 they adopted the European Ethical Charter on the use of Artificial Intelligence in judicial systems and their environment [2].

To implement AI solutions in justice systems it is necessary to consider the impact of legal AI solutions to the entire society. This is aligned with the obligation of judges to "learn about the environment and living conditions of judicial system users" aimed at increasing "knowledge of social groups and their dynamics so that their decisions can be based on those realities" [3; p.18]. Therefore, judicial decision making goes beyond pure and strict implementation of legal acts especially because not everything can be prescribed.

This article puts the justice systems and AI implementation in the context of cybernetics and stresses the importance of making a whole picture of socio-technical impact of introduction of new technologies. It explains the justice system as a set of business rules that are prerequisites for defining and design of any new information system. Furthermore, as cybernetics can be viewed as an explanatory framework of a large socio-technical system, AI implementation is explained through elements of socio-technical system.

CYBERNETICS AND THE LAW

Cybernetics can be viewed as a discipline of systems science with the purpose to explain goal-directed behaviour from the perspective of control and information [4; p.3]. As such, this concept can be applied to all systems, from organic systems to social systems. Father of cybernetics, Norman Winer, coined the term "cybernetics" based on the Greek word kubernētēs or steersman [5; p.15]. Cybernetics provides the theoretical framework for explaining the creation and maintenance of order in various systems. The crucial mechanism of maintenance of order is the management of feedback [6]. Cybernetics is the study of feedback and its influence on systems of interest. The essence of cybernetics can be depicted through cybernetic feedback loop, Figure 1.

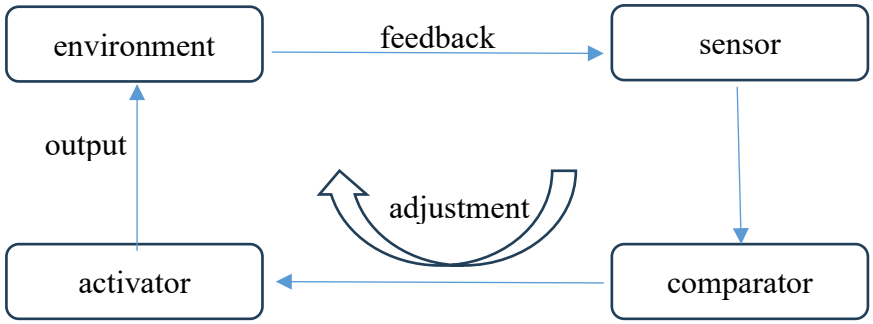

Figure 1. Cybernetic feedback loop [7].

Although cybernetics is usually viewed as a technical discipline, it can be said that it is complementary to the rule of law. Throughout history laws represented tools to impose order and control over societies and to "guide behaviour in a way that make complex relations more predictable" by giving "standards that people can refer to and means of making decisions" [8; p.12]. The bottom line is that while cybernetics deals with the nature of business rules, legal systems deal with the implementation of business rules (legal norms). Therefore, the cybernetic feedback loop that includes the justice system can be depicted as follows:

- the environment represents a society in larger sense that includes individuals, lobby groups and political parties,
- feedback is public opinion,
- sensors are members of the society that point out to possible issues that are consequence of activities of an individual or different social groups,
- comparator, usually government agencies, law enforcement bodies, etc. use information from the comparator to initiate necessary adjustment,
- activator, it this case judicial system, explains and implements the legal norms (business rules),
- output in a form of a judicial rulings and opinions influence the behaviour of the society who, if necessary adjusts the legal norms.

The potential of application of cybernetic principles in judicial system was recognized in the early 1960's by Kerimov [9]. Today, we can talk about the sub-discipline of cybernetics referred to as legal cybernetics. Legal cybernetics focuses on the judicial decision, or transformation in the cybernetic sense. In that context the judge makes a selection of relevant legal norms or precedents and applies specific content related to the given case, and finally identifies the legal consequences based on evidence and circumstances, Figure 2 [10].

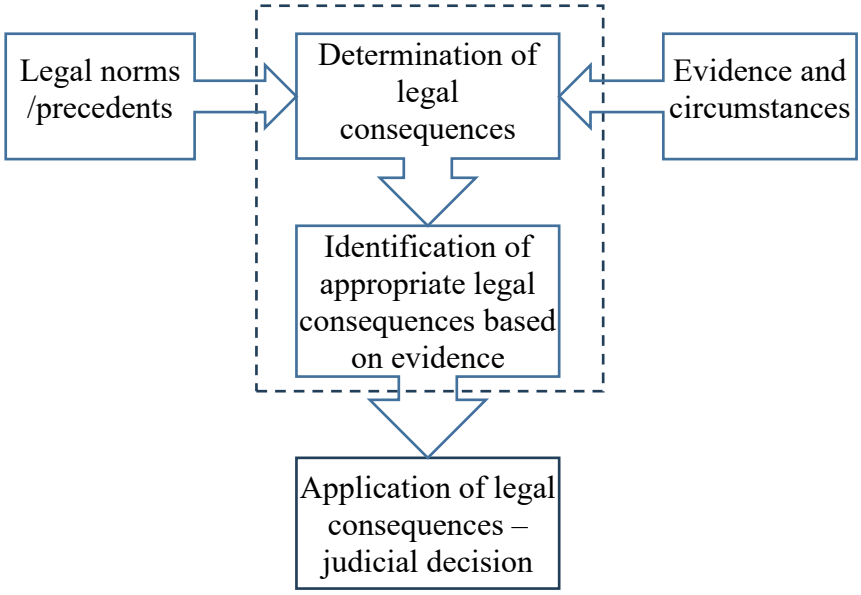

Figure 2. Logical structure of judicial decision making.

LEGAL SYSTEM AS A SET OF BUSINESS RULES

Business rules can be defined as a constraint that defines if something is under certain conditions. true or false [11; p.6]. For example, in MS Excel they can be expressed with conditional functions IF, AND, OR and NOT (latest three called Boolean logic operators). They can be divided into two general types [12], constraint rules and derivation rules.

CONSTRAINT RULES

Constraint rules represent a constraint condition that guarantees that certain conditions are met so that certain functions can be carried out. These rules can be further divided into stimulus and response rules, operation constraints and structure constraints. Stimulus and response rules are applied when predefined conditions are met. Operation constraint rules refer to conditions that must be true before and after the activity or operation. Structure constraint rules is a broader concept that represents the existence of relationship between two objects.

In legal terms the rules can be applied as follows:

- Stimulus and response rules – if the driver have passed red traffic light without causing an accident he should be fined XY amount of money and his driving license will be taken on the period of three months.
- Operation constraint rules – if the business has revenue of less than 1 million euro it will be taxed at a 10 % rate. If the revenue is larger than a million euro, then the business will be taxed at an 18 % rate.
- Structure constraint rules – only the active parties and the judge in the litigation can have an electronic access to court documentation.

DERIVATION RULES

Derivation rules are the outcome of a combination of constraint rules. In other words, they apply several different criteria for performing specific activities. Von Halle and Goldberg define derivation business rules as "an expression that evaluates facts, by means of a calculation or classification, leading to a new fact (i.e., conclusion)" (as presented in [13]). They can be subdivided into inference rules and computation rules. Inference rules are derived from constraint rules and after the validation that the specific facts are true, they lead to a particular conclusion. Computational rules are the result of algorithms. Again, in legal terms the rules can be applied as follows:

- Inference rules – inference rules are applied in common law systems through *res ipsa loquitur* doctrine – the thing speaks for itself. This doctrine is based on the premise "that circumstantial evidence of a particular kind can support a finding of liability" [14]. The best example would be that of medical negligence; if a surgical instrument is left inside a patient after surgery, the mere fact that the instrument was left inside the body can infer negligence without needing further specific evidence of the surgeon's actions.
- Computational rules – all cases that involve calculation of damages would be examples of computational rules. For example, in criminal cases, all calculations related to the value of tax frauds are based on computational rules.

ARTIFICIAL INTELLIGENCE, BIG DATA AND THE LAW

As discussed before, the essence of the legal system is the implementation of business rules. Business rules are represented by legal acts. These acts represent the legal norm, and it is expected that the principle of *iura novit curia* is applied. In other words, it is assumed that the judge knows the law while parties involved in the court case are in charge of providing facts (evidence) [15]. Here it must be noted that this principle traces its origins from Roman law although it is less present in common law jurisdictions [16].

BIG DATA

Court cases are sophisticated not just because of the abundance of evidence but also because of the quantity of legal acts that are the foundation for the rulings in civil law systems. At the European union level there are 8 types of legal acts, some of which are not mandatory: EU treaties, regulations, directives, decisions, recommendations, opinions, delegated acts and implementing acts [17]. Furthermore, every member state has its constitution, laws, bylaws and ordinances. Under such circumstances, can it truly be expected that the judge will know the entire legal framework that is the foundation for making judicial decision? Therefore, when discussing judicial decision making, we are discussing a big data problem.

In common law systems, the situation is even more comprehensive because judges have two roles, that of the decision maker and the role of the law maker. What this means is that in

common law systems the judge must base his decision on case law or precedents which tend to be high in volume [18]; to do that he must be able to access the database containing all of previous rulings. Again, we face a big data problem.

Big data can be defined as "the generation and accumulation of data beyond given processing capabilities to the point that users are overwhelmed by it" [19]. Because of this, almost impossible to count all the legal norms in power or the number of precedents. Furthermore, judges often face the issues of applying legal norms that are no longer in power anymore which enlarges the set of rules that judge needs to be aware of to apply them to specific court cases. Therefore, legal norms and precedents fulfil the criteria of the three Vs of big data: volume, velocity and variety [20]. In other words, the quantity of legal norms and presented facts in the court case are beyond human processing capabilities. Consequences of the big data problem are that trials usually last long; either they require time for judges to navigate through the legal framework and presented facts or the trial is repeated based on appeal.

AI AND THE LEGAL PRACTICE

Artificial intelligence can be described as a system that displays "intelligent behaviour by analysing their environment and taking actions – with some degree of autonomy – to achieve specific goals" [21; p.19]. Although litigation and legal jobs are primarily based on human based work, according to the study on use of AI in legal practice carried out by The British Institute of International and Comparative Law, AI is already present in seven areas of legal work: e-discovery, automation of the documents, predictive analytics, legal review, case management tool, automation of legal advices and expertise and knowledge management and marketing [22; p.2]. In spite of these abilities, AI is still not widely present in legal firms; only 3 % of law firms in the US, UK and Canada use ChatGPT/generative AI for firm operations, and 60 % do not even consider to use it in the near future [23; p.12]. On the other hand, 67 % of 1200 individuals from North and South America and UK working in the legal, tax & accounting, global trade, risk, and compliance fields stated that generative AI will have a high and transformational impact in their field with law firms prioritizing productivity as their main concern [24]. It must be stressed that although AI systems in judicial systems or legal practices are humbly used, there are already several generative AI tools present on the market:

- Westlaw Precision for legal research with CoCounsel AI legal assistant [25],
- Lex Machina legal case analytical tool and trend predictor [26],
- Everlaw Assistant - able to make first drafts and depositions with argumentation [27],
- Harvey AI – large language model (LLM) system aimed at assisting lawyers in legal research [28].

CYBERNETIC VIEW OF AI IN THE LAW

Artificial intelligence systems, in essence are highly sophisticated information systems and as such they represent a tool that simply aids humans in their work. That aid goes beyond simple automation of routine activities. Automation of legal advice and case management tools require a system with intelligent behaviour. In legal professions that is not enough. What is necessary is human supervision, where the human has a steering role. In the near future humans will have an inevitable role in legal practice despite the increased role of AI, primarily because of rising ethical and moral issues related to use of AI technologies. It can be expected that legal professionals will start working as members of human-agent teams sharing tasks with AI systems [29]. That situation will lead to the transformative role of AI. Narrowly viewed, certain level of job loss in different sectors and legal systems can be expected, but from the societal perspective, the application of AI in legal sectors will lead to job shifting [30] consequently creating new jobs, predominantly in the IT sector.

Taking the cybernetics perspective on AI, its implementation beyond a pure technical or engineering perspective should be considered as a part of a larger socio-technical system. The entire socio-technical system is comprised of number of elements including "technology, science, regulation, user practices, markets, cultural meaning, infrastructure, production, and supply networks" [31]. Therefore, implementation of AI systems in justice systems has a much broader impact than just making the legal system more efficient. Widely known maxim, "Justice delayed is justice denied", directly affects user experience and perception of fairness of the justice system [32]. Therefore, the inefficiency and slowness are primary reasons for the mistrust in the justice system [33]. In that manner, implementation of AI in justice system should be aimed at increasing efficiency.

Development of a large-scale AI solution for justice systems technically is the same as development of any other LLM's and it is called training. Some authors propose training of LLM's in three phases: data collection and processing, the pre-training process, and fine tuning and alignment [34]. But more appropriate is the six-step methodology suggested by Suresh and Guttag that consists of data collection, data preparation, model development, model evaluation, model post-processing and model development [35].

Apart from the LLM developmental phases, implementation of AI in justice systems requires intervention in all other elements of socio-technical systems. First off, all business rules should be transformed, and regulatory framework should be adapted to all possible uses of intelligent systems in civil and criminal cases that directly influence user practices. For example, cases related to minor violations such as traffic violations can be fully automated. Such implementation would reshape justice system markets as the consumers (parties in civil and criminal cases) would become more demanding. Research on implementation of AI in accounting services points out that clients will "expect services to be more cost-effective, faster, and more efficient. These expectations will be paired with clients setting a higher bar for cybersecurity and compliance" [36]. According to the same research, accountants fear that introduction of AI will diminish personal touch with the clients and degrade skills of the professionals.

Increasing efficiency should be implemented through transformation of business rules through:

- Transformation of user practices – how stakeholders (lawyers and judges) do their jobs. I.e. AI systems could be used to automate writing minutes from trial sessions and coordination of online trial sessions.
- Transformation of production and supply networks – the process of collecting evidence, necessary facts and making court filings according to collected facts.
- Update of regulatory framework – this is maybe the most challenging element of a socio-technical system because it raises not only legal but also ethical issues. As such, it can pose the biggest barrier to widespread introduction of AI to justice systems. The complexity of defining appropriate regulatory framework for introduction of AI systems can be best presented on the example of introduction of autonomous vehicles that are still not commercially present on roads in most parts of the world mainly due to non-existent unified regulation related to use of the unmanned vehicles [37]. Here it must be stressed that the judicial system is more sophisticated and has a much bigger impact to society as a whole.

Infrastructure is another element that consists of all necessary physical resources that are needed for a functioning socio-technical system [38]. Although it is a crucial prerequisite for the implementation of AI in justice system, infrastructure is developed independently due to a surge in general data demand. Such a surge can be directly related to the usage of LLM's, such as ChatGPT, that reached one million users in only five days [39]. To put that in data perspective – a complex information system for medical radiology bases it's functioning on approximately 300 million parameters while LLMs like ChatGPT need at least a trillion

different parameters to function as expected [40, 41; p.4]. Such data processing requirements can be served adequately only by server farms or by distributed systems. Apart from increased computational demands, increased use of generative AI puts the pressure also on network bandwidth, security measures, power supply, and distribution network [42].

Market elements of socio-technical system solutions is closely related to cultural meaning. AI market is expected to rise to total of 1811,8 billion USD by 2030. This increase will greatly impact the Chinese economy at a total of 26,1 % GDP, then North America (14,5 % of GDP), Southern Europe (11,5 % of GDP) , developed Asia (10,4 % of GDP), and then Northern Europe (9,9 % of GDP) [43]. In other words, it can be said that among developed countries around the world AI systems have the most acceptance in China and the least acceptance in Europe. The reasons for that can be traced to more a conservative approach to general legislation related to information technologies. In that manner, EU recently endorsed the Artificial Intelligence Act – universal regulatory framework for general implementation of AI in all EU member states [44]. The emphasis of that act is the protection of public interest through setting strict AI implementation standards.

So far, the US does not have such comprehensive federal regulation; although there is a number of proposed laws related to the regulation of use and development of AI [45]. It is important to mention that in the US the White House Office of Science and Technology Policy published The Blueprint for an AI Bill of Rights that is “a guide for a society that protects all people” from AI threats [46]; but that Blueprint is not enforceable by law or in any way legally binding. On October 30 2023 president Joe Biden issued the Executive Order on the Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence [47], that is aimed at regulating the implementation and responsible use of AI, but it is not as strict as the Artificial Intelligence Act, especially because it lacks data privacy regulatory framework [48]. Because the laws are a consequence of societal values, they do not represent just regulatory framework of sociotechnical system but also the cultural one. Together, these two elements define the prospects of the market. Referring to the justice systems, it can be expected that introduction of AI would be slow because of cultural elements, with better acceptance in Common law systems (like the USA) than in Civil law systems (like Europe). This is also evident through the number of AI-related bills passed into law where the USA is the leader [49; p.267].

Based on all socio-technical elements, it can be concluded that the large scale introduction of AI in justice systems will be slow primarily due to social elements of the system. Another reason for slow introduction of AI in judicial systems lies in insufficient theoretical research of the relationship between the law and information systems where current research is focused mainly to organizations and not to the macro level [50]. Furthermore, the legal profession is conservative because the functions of lawyers and judges “are those of conservators of certain values of the past which have proved to be worthy of preservation” [51].

CONCLUSION

With the emergence of LLMs and sudden widespread use of generative AI systems in many different fields, AI is often viewed as a solution to all problems with the prospects of improving and ultimately replacing work of many professionals. Implementation of AI in justice systems offers the same opportunities but there are still many obstacles resulting from the social side of justice systems to overcome. Apart from transformation of existing business rules on which justice systems are based, the major efforts should be aimed at facing the non-technical issues of AI implementation such as fear of AI, conservativism of legal experts, and making appropriate regulatory framework. Consequently, it can be expected that the justice systems will be among the last areas of human activity to join the AI revolution.

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THE USE OF ARTIFICIAL INTELLIGENCE BY YOUNG ENTREPRENEURS IN THE REPUBLIC OF CROATIA

Mladen Rajko*

University of Zadar, Department of Economics
Zadar, Croatia

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ABSTRACT

This article examines the growing significance of artificial intelligence (AI) in the entrepreneurial ventures of young entrepreneurs in the Republic of Croatia. Through surveys and interviews with young entrepreneurs from various economic sectors, the study identifies the most frequently used AI tools and assesses their impact on business success. The findings indicate that while AI has the potential to revolutionize business processes, enhance decision-making, and improve efficiency, its adoption among young entrepreneurs is still inconsistent. Many entrepreneurs hesitate to fully integrate AI due to challenges such as high costs, lack of technical expertise, and ethical concerns. Despite these barriers, those who do use AI often apply it to tasks like content creation, social media management, and financial reporting, highlighting AI's ability to streamline operations. However, the current level of AI adoption among young entrepreneurs remains insufficient to drive a major shift toward digital entrepreneurship. To fully unlock AI's potential, the article suggests that targeted educational initiatives and resources tailored to young entrepreneurs are crucial. These efforts could bridge the knowledge gap and reduce perceived risks associated with AI. The article concludes by emphasizing that while AI offers significant opportunities for enhancing business capabilities, overcoming existing obstacles is essential. By addressing these challenges and fostering a supportive environment, there is substantial potential to drive innovation and success in the entrepreneurial sector. Future research should continue to explore AI adoption dynamics and broader implications, ensuring that young entrepreneurs are prepared to thrive in an increasingly digital world.

KEY WORDS

artificial Intelligence, AI, young entrepreneurs, AI tools, Croatia

CLASSIFICATION

JEL: L86, O31

*Corresponding author, η: mrajko@unizd.hr; -;
University of Zadar, Department of Economics, Splitska 1, HR – 23 000 Zadar, Croatia

INTRODUCTION

In today's dynamic business environment, artificial intelligence (AI) is becoming an increasingly important tool for young entrepreneurs who want to improve their business processes, increase efficiency, and achieve a competitive advantage. This article explores using artificial intelligence tools among young entrepreneurs, focusing on their choices, experiences, and challenges. AI is expected to positively impact young entrepreneurs, improving opportunity recognition, decision-making, performance, education, and research while bringing challenges such as potentially damaging social and economic implications for traditional small businesses. AI is increasingly recognized as a transformative tool in entrepreneurship, especially for young entrepreneurs. Integrating AI into entrepreneurial activities will improve various aspects of the entrepreneurial process, from identifying opportunities to optimizing decision-making and business results. AI platforms enable young entrepreneurs to improve digital skills, organize finances, and recognize different types of intelligence, thus creating a stimulating digital environment. Also, it is expected that AI algorithms can offer new solutions to face challenges in entrepreneurial environments, improving creativity and judgment. Considering that research on the application of artificial intelligence among young entrepreneurs is a relatively new field, it is expected that further research will single out several vital works and authors that will contribute to the development of this field.

The research was initiated due to the increasing use of AI in business, emphasizing young entrepreneurs in Croatia. While AI offers opportunities to improve efficiency and innovation, its adoption among young people is uneven due to high costs, lack of technical expertise, and ethical dilemmas. The innovativeness of the research lies in the specific focus on regional entrepreneurs and the tools most often used in their business processes, providing insight into opportunities and challenges in integrating AI. The research's purpose is to analyze the use of AI among young entrepreneurs and determine how these tools contribute to business success. Objectives include identifying the most commonly used AI tools, analyzing barriers to their implementation, and proposing educational initiatives and policies. These are crucial for promoting the wider application of AI and are key outcomes of this research. This study significantly contributes to a better understanding of AI's role in Croatia's digital entrepreneurship development. The research included a survey and interviews with young entrepreneurs from various economic sectors in the Republic of Croatia to gain insight into which UI tools they use most often and how these tools contribute to their business success. The research results reveal trends in the application of artificial intelligence among young entrepreneurs, as well as specific tools that have proven to be the most useful in their business. In the continuation of the work, the most frequently used tools will be presented and analysed in detail. The goal of this article is to provide a deeper understanding of artificial intelligence's role in young people's entrepreneurial initiatives and to encourage the further application of these technologies to improve business results.

It is assumed that AI algorithms can offer new solutions to solve challenges in the business environment, improving creativity and judgment. Research into the application of artificial intelligence among young entrepreneurs is a relatively new field, and it is necessary to highlight several of the most important papers and authors.

Giuggioli and Pellegrini [1] claims in the research that artificial intelligence positively affects entrepreneurs through opportunities, decision-making, and the effect of education and research. Adnan [2] argue that an AI-powered online platform helps future digital entrepreneurs improve their digital skills, streamline their finances, and recognize multiple intelligences. After conducting research, Chalmers, MacKenzie and Carter [3] stated that AI can improve entrepreneurial activities. However, it can also have negative social and economic implications, especially for traditional small companies threatened by disintermediation. Obschonka and

Audretsch [4] prove that artificial intelligence and big data can contribute to the productive transformation of youth entrepreneurship research and real-world phenomena such as "smart entrepreneurship". Townsend and Hunt [5] say in the paper that AI algorithms provide new solutions for solving the challenge of modal uncertainty in the entrepreneurial decision environment, creating new possibilities for future forms of entrepreneurial action.

Taking into account the research carried out by the European Union, according to the published research results (Eurostat, accessed August 17, 2024) [6], in 2023, 8% of EU companies with ten or more employees used AI technology to run their business. The application of artificial intelligence refers to systems that use technologies such as text mining, computer vision, speech recognition, natural language generation, machine learning, and deep learning to collect and use various data to make predictions, recommendations, or decisions – with levels of autonomy – the best actions to achieve specific goals. Denmark (15,2 %), Finland (15,1 %), and Luxembourg (14,4 %) had the largest share of companies with ten or more employees using AI technologies. The most minor shares are recorded in Romania (1,5 %), Bulgaria (3,6 %), Poland (3,7 %) and Hungary (3,7 %). The following graph shows companies with over ten employees using AI technologies in the European Union in 2023.

The Global Entrepreneurship Monitor [7], a pioneering research initiative founded in 1999, is the largest and most comprehensive of its kind. It tracks entrepreneurial activities, aspirations, and attitudes of individuals in different countries. One of its key contributions is the use of the category' young entrepreneurs' for individuals aged 18 to 34 in its research and reports on entrepreneurship. This category, while flexible in academic research, often spans the 18-35 age group, covering the various stages of entry and establishment in the business world. The European Agricultural Fund for Rural Development, for instance, defines youth as all those under 40. Given these varying perspectives on the age limit for young people and the unique characteristics of young entrepreneurs in the Republic of Croatia, the authors made a deliberate decision to focus their research on young entrepreneurs up to 40 years of age.

The article is structured so that after a short summary, it begins with an introduction, where the importance of AI in entrepreneurship is explained, especially among young entrepreneurs, and the challenges they face are highlighted. The research methodology follows a detailed description of the research methods used, the sample of respondents, and the data collection process. The article's core is analysing the results, where data from surveys and interviews are presented. This section explores the most commonly used AI tools, their advantages, and their application challenges, providing a comprehensive understanding of their role in entrepreneurship. The article concludes with a summary of key findings, recommendations for future research, and suggestions for encouraging the broader application of AI among young entrepreneurs. A list of literature, which includes the sources used in the research, is provided at the end.

ARTIFICIAL INTELLIGENCE APPLICATIONS USED BY YOUNG ENTREPRENEURS

AI represents one of the most significant technologies shaping the modern world, including entrepreneurship. While AI has existed in large companies for many years, young entrepreneurs increasingly recognize its potential for creating innovations, increasing efficiency, and improving business. This chapter investigates to what extent young entrepreneurs in the Republic of Croatia use artificial intelligence tools and which tools they are. Artificial intelligence encompasses a wide range of technologies that enable machines to "learn", "think", and "act" in a way that mimics human intelligence. These include machine learning, natural language processing, computer vision, and other advanced methods. In business, AI automates processes, analyses large amounts of data, predicts market trends, and personalizes customer experiences [8]. For young entrepreneurs with limited resources, AI can

provide a competitive advantage by enabling faster and more efficient decision-making. Young entrepreneurs, often characterized as tech-savvy and innovative, naturally gravitate toward AI for several key reasons (adapted by the author according to [9]):

- AI enables business scalability, which is especially important for startups aiming for rapid growth.
- Young entrepreneurs tend to experiment and embrace new technologies, making them ideal candidates for pioneering AI applications.
- Digital transformation and the growth of the digital economy require AI to remain competitive in the market.
- Young entrepreneurs recognize AI as a tool for solving global challenges, such as climate change, through smarter and more sustainable business models.

AI enables the automation of routine tasks, which is crucial for small teams with limited resources. Young entrepreneurs use AI to automate administrative tasks, manage inventory, optimize marketing campaigns, and manage customer support via chatbots [9]. For example, chatbots, guided by natural language processing algorithms, can quickly and efficiently respond to user inquiries, saving time and increasing customer satisfaction. One of the most prominent applications of AI in business is personalizing the customer experience. Young entrepreneurs use AI to analyse user data and adapt offers, recommendations, and marketing messages to the specific needs and interests of users. This strategy is particularly effective in e-commerce, where personalization can significantly increase conversion rates and customer loyalty. Startups often implement AI systems that learn from user behaviour and predict their future needs, thus creating a deeper connection between the brand and the customer [3]. AI enables young entrepreneurs to make informed decisions by analysing large amounts of data. Instead of relying on intuition or limited information, AI tools can process complex data sets and identify patterns and trends that would otherwise go unnoticed. This approach is used in finance, marketing, demand forecasting, and risk management.

AI also plays a crucial role in product and service innovation. Young entrepreneurs use AI to develop innovative, adaptable products better suited to market needs. AI enables young entrepreneurs to optimize marketing campaigns through data analysis and automatic message adjustment. AI systems can segment the market, target specific demographics, and tailor content based on user behaviour. Also, AI can help identify the most effective channels and time frames for advertising, resulting in higher conversion rates and lower advertising costs. While AI offers significant benefits, its adoption can be expensive, especially for young entrepreneurs with limited budgets. The costs of developing, adapting, and maintaining an AI system can be significant, and the return on investment is only sometimes immediately visible. Implementing AI technologies requires specific technical knowledge that many young entrepreneurs may need to gain. Finding qualified experts to develop and implement AI solutions can be challenging, especially in the early stages of a business. AI raises ethical issues, especially when collecting and processing personal data. Young entrepreneurs must navigate complex legal and ethical requirements to ensure that their AI solves problems.

EMPIRICAL RESEARCH

In order to obtain as relevant data as possible, research was conducted in the form of surveys and interviews, and the research methodology, sample, and research results are explained in more detail further in the text.

METHODOLOGY AND SAMPLE

The research was conducted over two months in May and June 2024. The research used a structured quantitative method (e-mail questionnaire) and a descriptive unstructured qualitative

method. To obtain relevant data for processing, the authors, in cooperation with the students, reached the contacts of 500 young entrepreneurs from the area where the authors and students are from (Istria, Primorje-Gorski Kotar, Ličko-Senjska, Zadarska, and Šibenik) -Knin County) so that the students should detect about twenty young entrepreneurs in their immediate environment. Out of 500 survey questionnaires, 80 were sent to young entrepreneurs in Istria County, 80 in Primorje-Gorski Kotar, 40 in Lika-Senj, 220 in Zadar, and 80 in Šibenik-Knin County. A total of 312 responses were received: 58 from Istria, 46 from Primorje-Gorski Kotar, 25 from Lika-Senj, 133 from Zadar, and 50 from Šibenik-Knin County.

The questionnaire consisted of 18 questions, 15 of which were of a more straightforward type. These questions included whether they had encountered artificial intelligence tools, which tools, how they got information about them, and how often they used them. The other three questions were more complex, and respondents were asked to state their biggest problems and challenges in business and whether they knew which artificial intelligence tools could help them in this.

Individual interviews followed the survey, the aim of which was to collect qualitative data about the experiences of young entrepreneurs with artificial intelligence tools, the difficulties they encountered when using them, and their suggestions related to the use of artificial intelligence tools by young entrepreneurs. 15 interviews were conducted in Istria County, 13 in Primorje-Gorski Kotar, 8 in Ličko-Senj, 48 in Zadar, and 16 in Šibenik-Knin – 100 interviews.

Table 1. Sent and received questionnaires and conducted interviews.

County	Questionnaire sent	Questionnaire Received	%	Conducted interviews
Istria county	80	58	73	15
Primorje-Gorski Kotar county	80	46	58	13
Lika-Senj county	40	25	63	8
Zadar county	220	133	60	48
Šibenik-Knin county	80	50	63	16
Total	**500**	**312**	**62**	**100**

Additional research was conducted using the Google search engine and the ChatGPT tool on the most frequently used artificial intelligence tools among young entrepreneurs in the European Union. The results of that research served as the basis for examining young entrepreneurs in the Republic of Croatia.

The results of this comprehensive research are detailed further in the text.

RESEARCH RESULTS

Based on the search of available information, the authors determined that the following artificial intelligence tools are most often used in young entrepreneurs' business within the European Union [10].

ChatGPT by OpenAI

It automates customer support, generates content, and assists in marketing. It is widely used for crafting engaging marketing messages and automating routine tasks.

Jasper

An AI-driven virtual assistant that helps with content creation, from blog posts to social media captions and even email marketing. It simplifies administrative tasks and boosts productivity.

HubSpot's ChatSpot.ai

An AI-integrated CRM system that helps entrepreneurs with customer relationship management, marketing and sales automation, and data analytics. HubSpot is very popular because of its adaptability and wide range of tools that make business easier.

Grammarly

A grammar and writing style checker that uses artificial intelligence to help entrepreneurs write accurate and stylistically correct texts. Grammarly is practical for everyday business communication and content creation.

Frase.io

An AI-powered tool for content optimization, improving SEO, and generating content briefs that help businesses rank higher in search engines.

Fireflies.ai

Transcribes meetings takes notes, and organizes action items, making it easier for teams to keep track of discussions and follow up on tasks.

Lavender.ai

Optimizes digital marketing campaigns by analyzing customer data and suggesting personalized strategies to improve engagement and ROI.

ThoughtSpot Sage

An AI-powered analytics platform that provides business insights by allowing users to ask questions in natural language and receive instant, actionable insights.

Tableau with AI integration

Visualizes complex data, allowing businesses to make data-driven decisions. The integration of AI enhances its predictive analytics capabilities.

Salesforce Einstein

An AI tool that helps businesses analyze customer data, predict behavior, and automate tasks within Salesforce's CRM platform.

These tools are popular among young entrepreneurs in the European Union because they offer significant time-saving benefits, improve decision-making through data insights, and enhance customer engagement through personalization and automation. These tools reflect the growing importance of AI in entrepreneurship across Europe, offering solutions that range from data analytics and customer interaction to content creation and marketing optimization. Entrepreneurs are increasingly adopting these technologies to stay competitive and foster business innovation. The following graph shows the use of artificial intelligence tools by young entrepreneurs in the Republic of Croatia on selected respondents.

Figure 1 shows that almost two-thirds of respondents do not use artificial intelligence tools in their business. Only 14 % regularly use them, 11 % occasionally, and 13 % have only tried them but do not use them often. The data processing of the analysed questionnaires resulted in findings on whether the respondents have used the most popular artificial intelligence tools in their business so far, as illustrated in Figure 2.

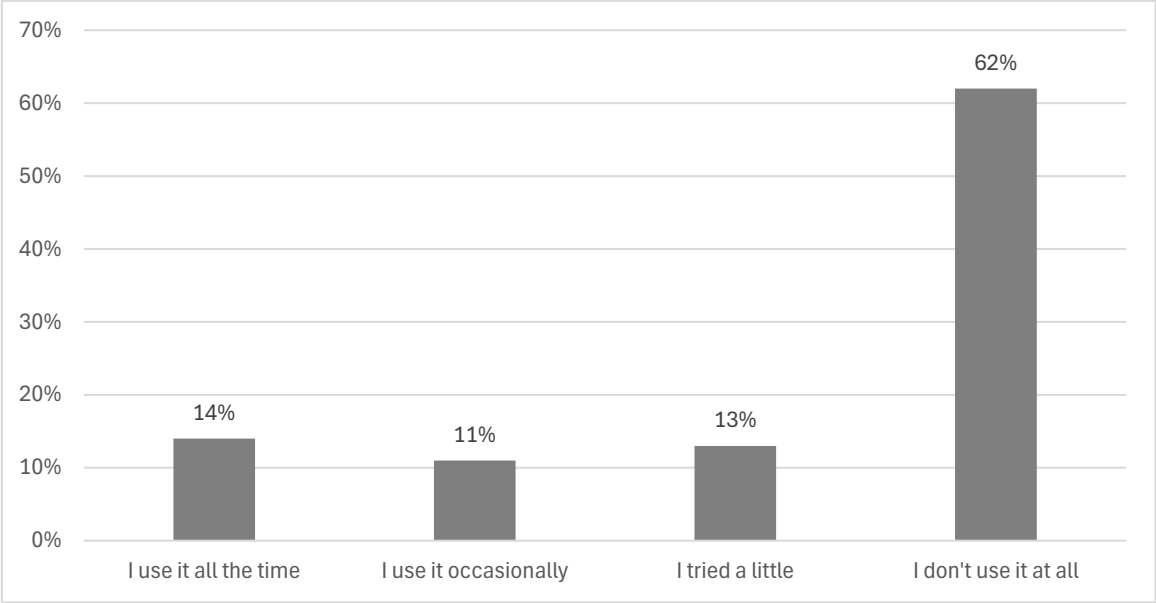

Figure 1. Use of artificial intelligence tools by young entrepreneurs.

Figure 2 shows that over twenty percent of young entrepreneurs had experience using the ChatGpt tool, and over ten percent used the Grammarly application. Tableau with AI Integration and the Salesforce Eistein application were the least used. A robust questionnaire was employed to gather the responses of young entrepreneurs who utilized AI tools, ensuring the reliability of the data. Figure 3 shows the respondents' answers regarding the purpose of using AI in the case when they use an artificial intelligence tool.

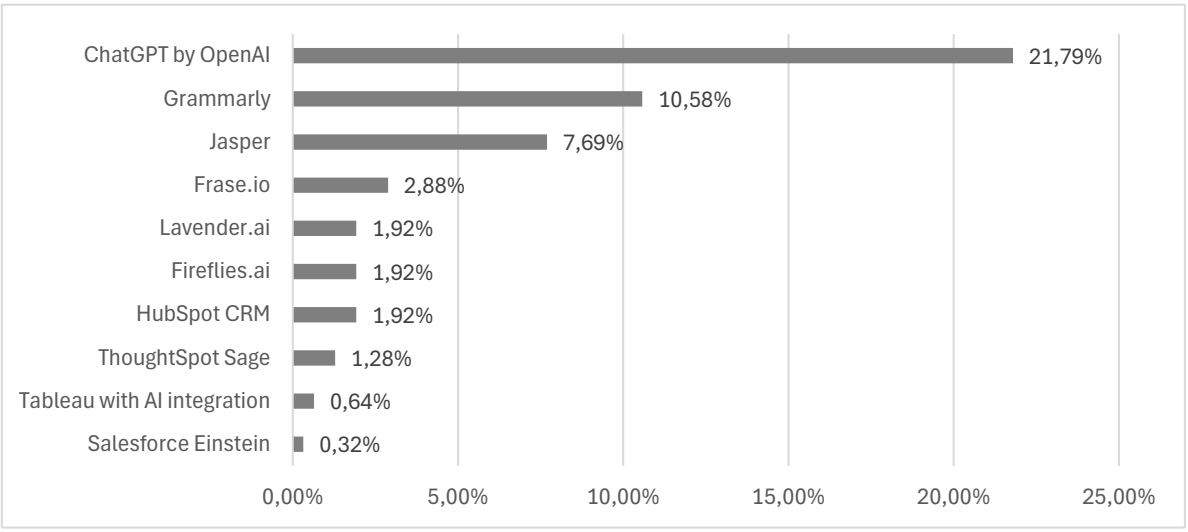

Figure 2. Percentage of use of artificial intelligence tools by young entrepreneurs, Croatia, 2024.

The research showed that young entrepreneurs who use artificial intelligence tools use them most for writing texts and planning trips, then for publishing various announcements on social networks and for writing financial reports, and least for shortening and reshaping text and preparing for interviews.

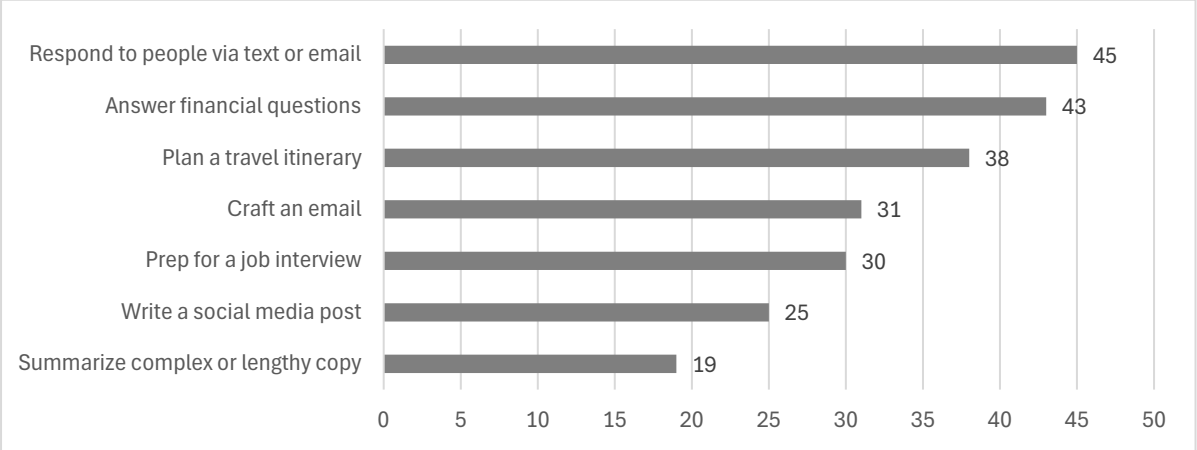

Figure 3. The purpose of using artificial intelligence tools among young entrepreneurs.

The interviews were conducted during May and June 2024. In cooperation with students, the author organized and conducted interviews with the target group of respondents. Each interview lasted between 45 and 60 minutes and was held in an unstructured format without transcribing data. For the analysis of the collected data, the method of content analysis was used, which includes classifying data according to terms with the aim of quantifying the data in such a way as to count the expressions and concepts that appear more than once.

Based on the data collected in the interviews about the experiences of young entrepreneurs with artificial intelligence, it is evident that their experiences are varied and often limited. While some young entrepreneurs recognize the immense potential of AI tools, especially in improving efficiency, automating tasks and saving resources, a large number of them are still not fully aware of the possibilities these tools provide. Respondents point out that the advantages of artificial intelligence are most visible in data analysis and marketing strategies, but many face numerous problems when trying to integrate them into everyday business.

Among the main problems that young entrepreneurs point out are the need for more specific knowledge about using AI technologies and the perception that these tools are complex, financially demanding, and require advanced technical skills. In addition, the lack of technical support and specialized education contributes to the problematic adoption of AI solutions. Many young entrepreneurs also point out that small businesses often need more resources to implement AI in business processes effectively.

Proposals of young entrepreneurs in relation to solving these problems include the urgent need for more accessible educational programs. These programs would be focused on the practical application of artificial intelligence in different sectors. Also, the need for the establishment of mentoring networks and technical support is emphasized in order to facilitate access to artificial intelligence tools for young entrepreneurs and to encourage wider acceptance of these technologies in order to achieve long-term business development.

DISCUSSION, CONCLUSION AND SUGGESTIONS

The research highlights the growing role of AI in the entrepreneurial endeavors of young entrepreneurs in Croatia. While the results demonstrate that some young entrepreneurs have successfully integrated AI tools into their business operations, the adoption rate still needs to improve. The main reasons for this include high implementation costs, a lack of technical expertise, and concerns over the ethical implications of AI. This aligns with findings in previous literature, such as those of Giuggioli and Pellegrini [1], who also noted similar barriers in AI adoption among entrepreneurs globally, particularly regarding resource limitations and knowledge gaps. One notable trend in the research is the preference for AI tools that assist with

routine tasks, such as content creation, financial reporting, and social media management. This mirrors the findings by Adnan [2], who identified similar usage patterns in other studies of digital entrepreneurs. However, it is interesting that more advanced AI applications, such as machine learning for business forecasting, should be utilized more. This may suggest that young entrepreneurs are still in the early stages of fully exploring AI's potential, a point also made by Obschonka and Audretsch [4].

From the author's perspective, AI has the transformative potential to revolutionize small and medium enterprises in Croatia, provided the right resources and support are in place. However, the reluctance to embrace AI due to technical and financial concerns underscores the need for robust educational programs and mentorship opportunities tailored to young entrepreneurs. These initiatives could effectively bridge the knowledge gap and mitigate the perceived risks of AI, thereby fostering wider adoption in the long run.

In conclusion, while AI offers significant opportunities for enhancing efficiency and competitiveness, its full potential among young entrepreneurs in Croatia remains largely untapped. This untapped potential should inspire and motivate young entrepreneurs to explore and adopt AI in their businesses. Future research could explore the development of specific educational programs and mentorship initiatives aimed at increasing AI literacy among young entrepreneurs, addressing both technical and ethical concerns. Additionally, studies could focus on identifying government incentives and policy frameworks that can lower the financial barriers to AI adoption, fostering wider integration of advanced AI technologies in business operations.

The research findings are crucial for further reflection on the potential use of artificial intelligence among young entrepreneurs. The fact that AI is still largely unknown to many young entrepreneurs, despite its recognition as a time-saving tool even among schoolchildren, is concerning. This gap in awareness is urgent and needs to be addressed to avoid hindering technological progress. However, for those already using AI, the ways in which they apply it offer a promising avenue for engaging more Croatian businesses. Since small business size is not a barrier to AI adoption, unlike other technologies, this presents an opportunity for faster technological integration. Moreover, this article could serve as a valuable resource for the young entrepreneur population in Croatia, motivating them to increasingly leverage available AI tools. By doing so, they can accelerate their long-term development and compete more effectively in both local and global markets.

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AN INFORMAL SETTLEMENT CASE STUDY – A SYSTEMS THINKING LOGIC APPLIED TO ENERGY POVERTY SITUATIONS

Perpetua I. Okoye*

University of Pretoria – Faculty of Engineering, Built Environment and Information Technology – Department of Engineering and Technology Management
Pretoria, South Africa

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ABSTRACT

This article applies a systems thinking logic to analyse energy poverty situations, using the Sofia informal settlement, a representative energy-poor community in South Africa, as a case study. Energy poverty in such communities transliterates into three interrelated energy poverty systems – material cultures, cognitive norms, and energy practices. The study investigates energy-related parameters and elements contributing to energy poverty in Sofia and similar informal settlements across South Africa. By adopting the systems thinking, these elements are identified and integrated into subsystems within the Energy Poverty Systems, modelled into the energy poverty model. The synergistic interactions influencing energy poverty are captured using causal loop diagrams. These diagrams offer a systems perspective on energy poverty analysis, providing actionable insights into critical gaps and intervention opportunities. The findings are intended to inform policies and tailored, inclusive interventions motivating sustainable energy access in informal settlements across South Africa.

KEY WORDS

energy poverty systems, energy poverty model, informal settlements, systems thinking, causal loop diagrams

CLASSIFICATION

JEL: N77, O13, Q41

*Corresponding author, η: pokoye04@gmail.com; -;
Department of Engineering and Technology Management, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

INTRODUCTION

Energy poverty is commonly defined as a lack of access to modern energy sources or reliance on inefficient fuels such as paraffin and charcoal, which limits households' ability to meet basic energy needs like lighting, cooking, space heating, and cooling [1]. While frequently linked to income poverty, energy poverty is a multifaceted socioeconomic issue shaped by a complex interplay of factors, including sociocultural environments that influence household energy-use patterns and behaviour [2]. Effectively analyzing energy poverty requires comprehensively evaluating the physical, sociocultural, economic, environmental, and institutional dynamics affecting an energy-poor group. Consequently, energy poverty analysis must go beyond technical algorithms and consider the diverse conditions and resources that define the realities of energy-poor communities.

South African cities have traditionally developed low-density suburban areas, often known as informal settlements or shacks – makeshift dwellings constructed without adherence to approved architectural plans – sprawling across the city's periphery [3, 4]. These settlements are predominantly inhabited by low-income households with limited access to essential utilities, such as energy, water, sanitation, and suitable housing [5]. Regardless of wether connected to the electricity grid, these households often rely on less efficient fuels [6] and adopt energy mixes, such as the concurrent use of electricity and paraffin for space heating in winter [7]. As such, these settlements serve as domains for understanding energy poverty situations in the region [8].

The situational analysis of energy poverty requires evaluating the diverse variables and their synergistic interactions that shape these situations in any energy-poor community [2]. These variables include elements central to energy poverty systems (EPSs), even at the subsystem level, describing energy use patterns, efficiency, preferences, productivity, affordability, and appliances. The synergistic analysis mainly involves mutual assemblages of these elements operating within these systems. Bridging the synergies between systems is critical to understanding energy poverty dynamics and necessitates the application of systems thinking (SsT) logic [9]. Classically, SsT is a set of analytical and synergistic skills designed to improve the ability to identify and understand systems, predict their behaviours, and implement modifications to generate the desired outcomes [10]. The core processes of SsT begin with identifying elements in a system, recognizing system purpose, and understanding the interconnections among its components [11]. These processes may include adding or removing elements to refine the knowledge of system behaviours, which can be reinforcing or dynamic. This further involves analyzing elements, flows, and non-linear interactions to gain an improved understanding of system behaviours. SsT views different facets of a system as single but different entities and bridges synergies using arrays of causal loops, linkages, and interactions. Central to SsT is the principle that a system is greater than the sum of its parts and should, therefore, be studied holistically. By modelling complexity - whether at the system or subsystem level – SsT helps elucidate behaviours and causal influences, encouraging a deeper understanding of patterns. With SsT, one can understand the primary causes of complex behaviours to enable adjustments of outcomes in energy poverty analysis.

The concepts of SsT [12, 13] and energy poverty [14, 15] have distinctive theories and operational needs. However, the evolution of SsT has shifted from product design to encompass systems of production and consumerism and a wide range of concerns across physical, sociocultural, economic, technical, and institutional domains [16]. Globally, energy poverty has been studied, [17-19], including in developing countries [20, 21] and specific South African regions [2, 3, 22-24], with its impacts extending across socioeconomic spheres, ethics [2], and the environment [25]. SsT has been applied [26-31] and recognized as an effective multi-criteria decision-support tool for energy access planning [10, 32]. As it is, informal settlements serve as perfect sceneries where energy poverty mitigation can be

promoted based on networking elements operating within the EPSs [33]. This underscores the importance of designing an autogenous, model-based SsT framework that describes system elements as integral components in analyzing energy poverty in informal settlements. The model's utility is to be committed to a place (in this case, informal settlements) by leveraging elements alleged to be activities within that place's spatial context integrable into modeling EPSs.

This article applies SsT logic to energy poverty by identifying and engineering elements in EPSs and their subsystems in the Sofia informal settlement as a case study. The goal is to provide a systems perspective highlighting interactions driving energy poverty situations in such contexts. In sequence, the article: 1) recognizes and integrates elements and subsystems into mutualistic EPSs and the energy poverty model (EPM) using SsT logic; 2) investigates energy-related parameters and elements in the settlement through empirical methods; 3) demonstrates the model's utility by empirically grounding significant elements and modeling system synergisms using causal loop diagrams (CLDs). The analysis offers a holistic understanding of energy poverty and insights to inform interventions addressing the challenges informal communities across South Africa face.

MATERIALS AND METHODS

APPLYING SYSTEMS THINKING: ENERGY POVERTY SYSTEM AND MODEL DEVELOPMENT

EPSs, comprising material cultures, cognitive norms, and energy practices, have been deconstructed into subsystems surrounding energy use [34], individual performance [35], and prospects for change in behaviour [36], Figure 1. These systems supported the goal of transformative change by simplifying the complexities of energy poverty dynamics and enabling flexibility in system configurations to observe potential impacts. SsT modeling of EPSs clarified the complexity of system behaviours and causal relationships embedded in the energy poverty model (EPM). The model development was guided by the need to ensure interoperability among physical, sociocultural, economic, institutional, and technological influences of energy poverty situations [37], promoting cohesive system operations toward shared goals. Each system can be analyzed in isolation but within the wider EPM modularity. The interfaces of these systems are critical as they interact dynamically to define the system functions, direct the system's purpose, and align with the model's overarching goals. The model aims to provide a systems perspective on energy poverty analysis, uncovering interactions that drive energy poverty in informal households and providing actionable insights for enabling energy access.

To capture the dynamics of energy poverty, diverse yet interrelated elements influencing behaviour were identified and integrated into the subsystems. The material culture system's subsystems encompass elements that describe energy poverty's physical, economic, and institutional influences, Figure 1. The energy use and sources subsystem represents all available forms and sources of energy within a target community. The house characteristics subsystem includes elements, such as dwelling types, house insulations, and renovations, directly impacting energy-use efficiency. The household income subsystem reflects income levels and the financial burden of energy costs on households. This system primarily shapes energy-use patterns and efficiency, and its interface significantly influences cognitive norms and energy practices.

The cognitive norms system comprises elements within subsystems that contribute to understanding the values, beliefs, and sociocultural, economic, and environmental inclinations shaping household energy choices, Figure 1. The expected comfort levels subsystem includes entertainment and meeting the minimum baseline of energy services required for daily living.

The social aspirations subsystem encompasses education/learning and entrepreneurship, reflecting aspirations that influence energy decisions. The respect for tradition subsystem evaluates the socio-cultural inclination toward energy choices, while the environmental and health concerns subsystem assesses awareness of poor energy-use practices and their impacts on well-being and the environment. This system largely shapes energy preferences and productivity, and its interface strongly influences material cultures and energy practices.

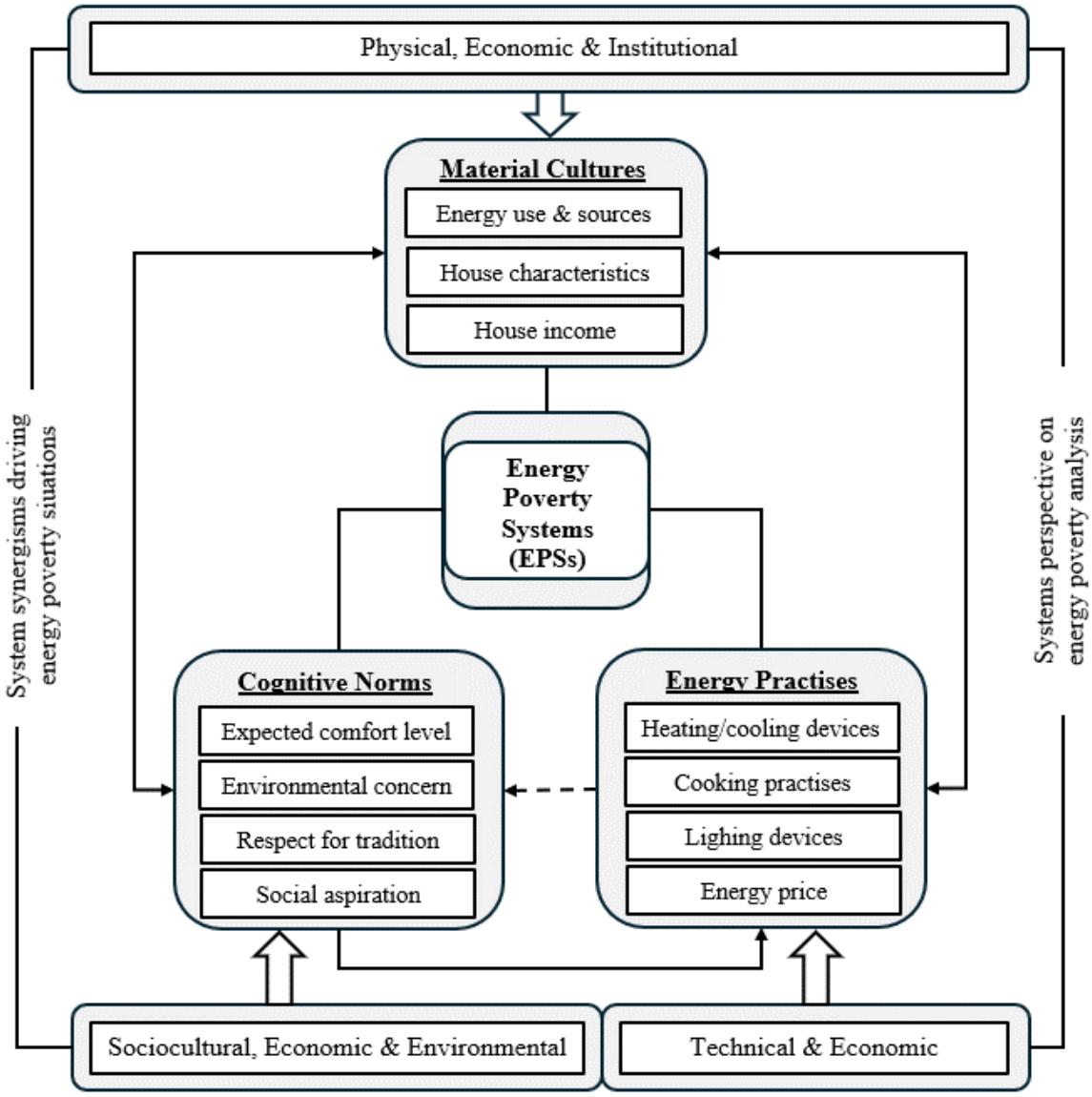

Figure 1. Energy Poverty Model Comprising Energy Poverty Systems. Strong (bold lines) and weak (dotted lines) connections represent high-level and low-level system dependency.

The energy practices system encompasses elements within subsystems that describe the technical and economic factors influencing energy poverty situations, Figure 1. The energy price structure subsystem is central in determining household adoption of clean energy fuels. The subsystem of heating devices includes paraffin and charcoal heaters, gas portable units, heat pumps, etc. Similarly, the cooling devices subsystem comprises window and door units and electric fans. The lighting choices subsystem involves paraffin lamps, candles, and light bulbs, while the cooking practices subsystem includes elements like paraffin stoves, gas stoves, and other cooking appliances. This system significantly shapes household decisions regarding energy appliances and pricing. While they strongly influence material cultures through system interfaces, their impact on cognitive norms is relatively limited.

CASE STUDY METHODOLOGY

The case study focuses on the Sofia informal settlement, a representative energy-poor community typically of many in Africa and Asia, located in the western part of South Africa, Figure 2. The settlement comprises about 200 to 220 informal households, predominantly occupied by low-income, black residents who are mainly unemployed and dependent on government grants. Despite being near the grid electricity, the settlement lacks access to electricity, a condition common in many informal settlements across South Africa. To understand energy poverty situations in the settlement, we conducted a primary survey using household questionnaires and semi-structured short interviews with local energy product vendors to investigate energy-related parameters and elements recognized within the EPSs and subsystems. The survey approach and analytical techniques used in this study are comprehensively detailed in [6].

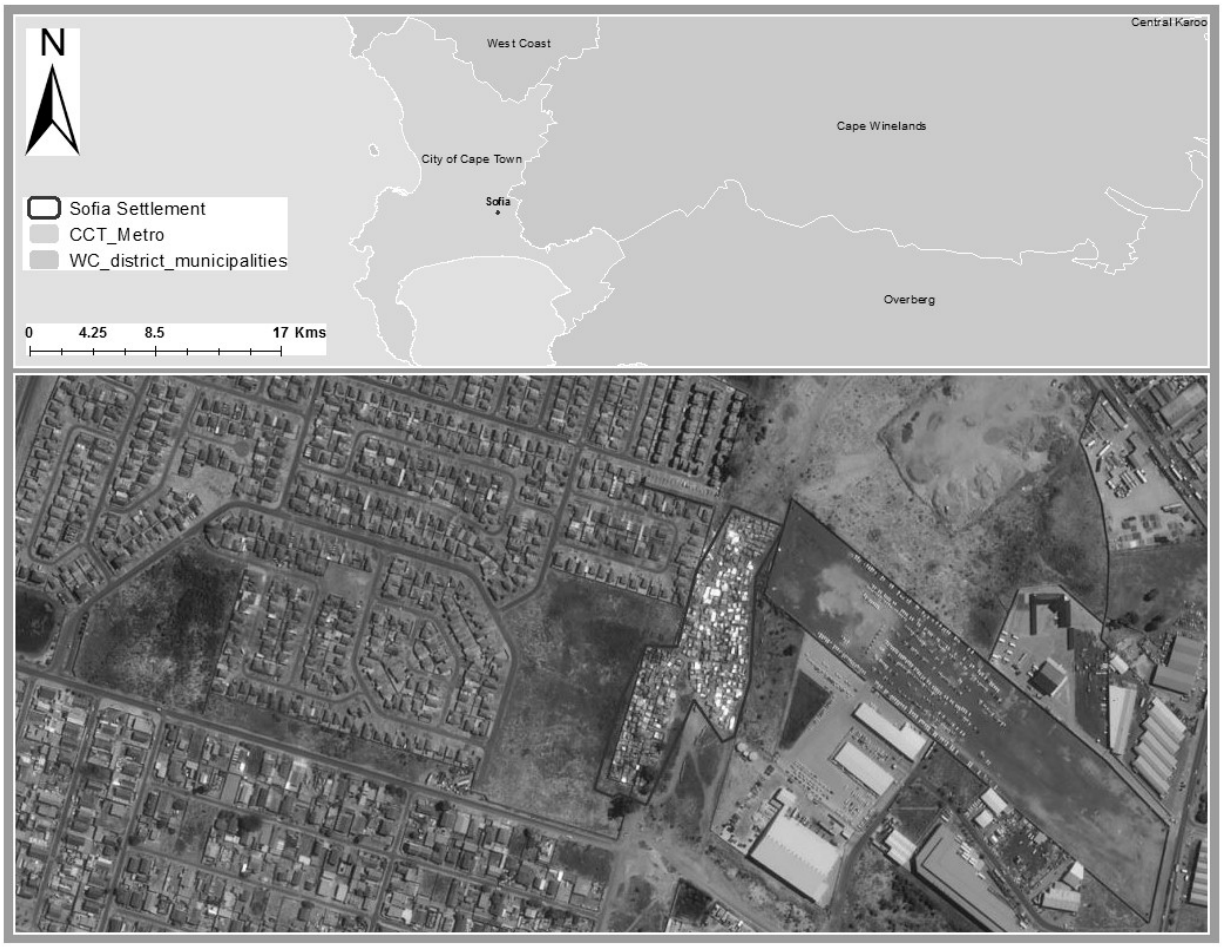

Figure 2. Case Study Area – Sofia Informal Settlement [6].

CAUSAL LOOP DIAGRAMS

Causal loop diagrams (CLDs) align with SsT in identifying, interacting with, predicting, and adjusting systems and behaviours, facilitating the modeling of variables operating within a system [33]. CLDs serve as illustrative descriptions of system synergisms, providing causal depictions, influences, and analyses while incorporating quantitative details about the nature of these influences [38]. CLDs were developed for distinct EPSs by connecting elements and subsystems through arrows, represented as causal loops and links [33]. Causal links, represented by single arrowheads and grounded on significant empirical outcomes from the case study, illustrate the basic mechanisms between subsystem elements. Causal loops, depicted with double arrowheads, reflect the reinforcing patterns (positive or negative) within

and between EPSs, emphasizing their systemic interactions. Connections in CLDs are categorized as strong (bold lines) or weak (dotted lines) and marked with + or - signs to denote high-level or low-level system dependency, respectively. Strong causal influences indicate that changes in one system are analogous to a similar change in another system, highlighting strong system coupling. Weak causal influences suggest that changes in one system induce changes in another with less intensity. While weak influences may not always drive system behaviour, they were treated as step inputs to broaden the understanding of elements and interactions influencing behaviour.

Using the Insight Maker online software, CLDs for individual EPSs were successively designed and built into the EPM. Annotations were employed to represent the systems: MCs – material cultures, CNs – cognitive norms, and Eps – energy practices. Causal loops within a system were labeled with the system's annotation, followed by a numeric identifier (e.g., MCs1), incrementing sequentially to reflect the total number of loops in that system. Loops spanning system interfaces were marked with annotations corresponding to all connecting EPSs linked by a hyphen (e.g., MCs-CNs). Significant and accurate data inputs, especially from a typical energy-poor community such as the Sofi settlement, were critical to ensuring the validity of insights generated in the model. The iterative CLD designs ensured the representation of EPSs evolved logically, focusing analyses on individual systems and capturing additional interactions at each step. The CLD development began with:

- Developing MCs; the initial step involved creating a simple CLD of a material culture system based on causal influences, including causal loops and links, to analyze the synergisms within the system.
- Incorporating CNs; the second step expands the diagram by integrating cognitive norms, resulting in additional causal loops and links and allowing for the analysis of synergisms within the CNs system and at the interface between MCs and CNs.
- Adding EPs; the final step involved integrating energy practices into the diagrams, generating further causal loops and links, and enabling the analysis of interactions within and across all three interfaces, progressively building these diagrams into the EPM.

RESULTS AND DISCUSSIONS

Table 1 in Appendix summarizes the case study data analysis, which organizes empirical findings by Okoye [6] under various energy-related categories. Each CLD design for distinct EPSs draws on sampled parameters and their significant outputs grounded in empirical evidence to update elements and causal influences in the EPM.

MATERIAL CULTURES

Figure 3 illustrates the initial step in mapping causal influences within the MCs system in a simple CLD. The diagrams highlight the interplay of subsystems and elements, revealing both strong and weak causal loops and links directed to influence CNs and EPs systems. In links, the MCs system was strongly defined by:

- Low-income households with no electricity access; predominantly used, separately and concurrently, less efficient energy fuels such as paraffin and gas (transitional or cleaner fuels) or candles (traditional or less clean fuels) for lighting. These fuels were:
  - readily available and accessible through local vendors,
  - consumed at monthly rates of less than 100 *l* for paraffin and within 100-250 *l* for gas.
- Monthly energy costs of about 50 % and 40 % (high) and 10 % and 5 % (low) of household income; however, low-income status and reliance on government grants [7] queried the high energy costs.
- Shacks, i.e., poorly constructed housing structures, mostly self-built, lacked insulation, rarely underwent renovations, and scarcely maintained warm temperatures in winter.

The first causal loop – MCs1, captured the synergistic interactions between energy use and sources subsystem and house characteristics subsystem, Figure 3. This loop, further influenced by MCs2 loop activities, revealed that significant influences of elements captured in links resulted in poor energy-use patterns (e.g., less efficient fuels and low energy demand levels) and efficiency (e.g., poor housing structures). The MCs2 loop linked energy use and sources with the household income subsystem, indicating how low-income status reinforced the adoption of less efficient fuels, primarily instigated by a lack of electricity access in the settlement. The MCs3 weak loop connected house characteristics and household income subsystems, indicating that the impact of one system does not equal the same effect on another. For instance, improving house efficiency does not equal household income and vice versa. However, the MCs3 strong loop was generated, driven by strongly linked elements such as household low-income and non-insulated homes, showing a positive reinforcing pattern between the subsystems. These causal loops jointly shaped the MCs system's overall behaviour, emphasizing the subsystems' interconnectedness in driving energy poverty situations within the settlement.

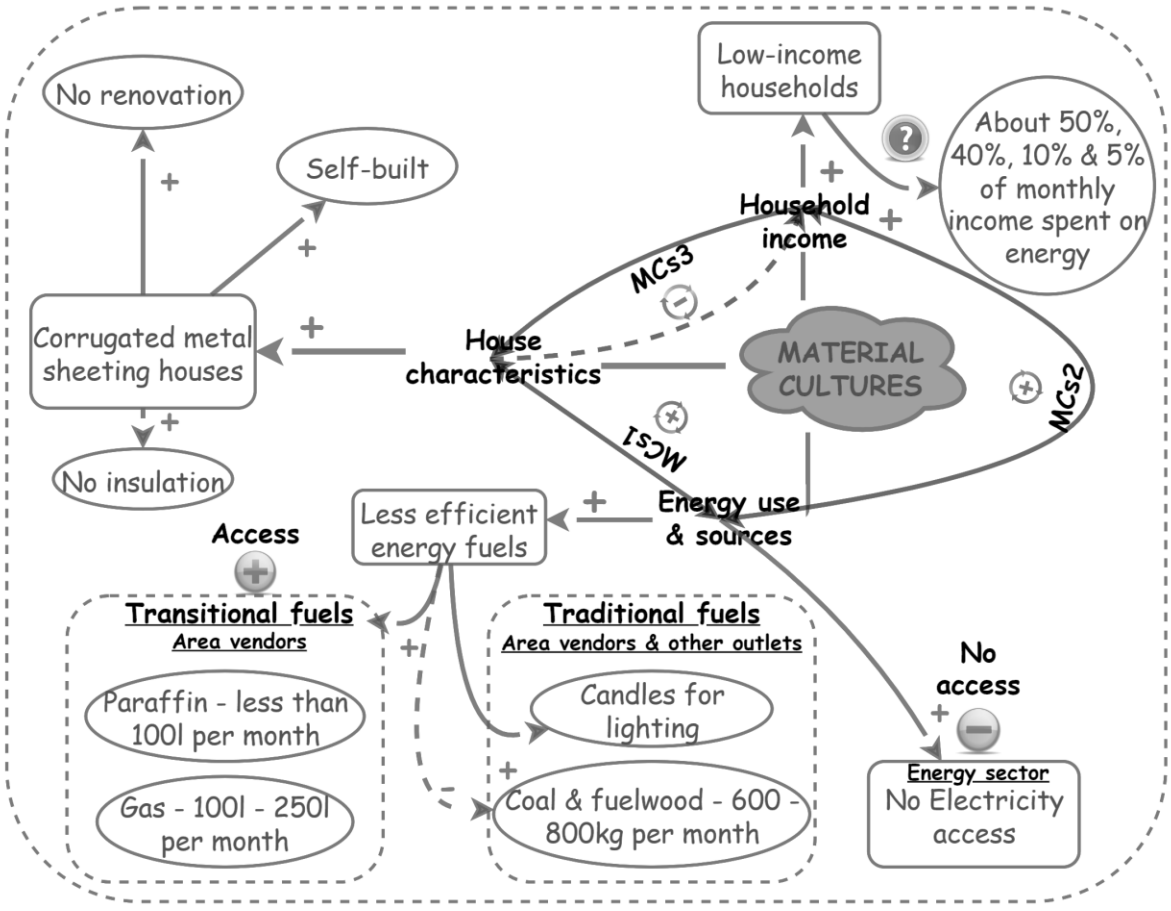

Figure 3. First Step: A simple CLD of MCs. Causal loops (in black) and links (in grey) are represented in strong (bold lines) and weak (dotted lines) connections, indicating high-level (marked with + signs) and low-level (marked with – signs) system dependency, respectively.

COGNITIVE NORMS

In the second step, the CNs system was added with a new set of causal loops and links to examine why households use energy the way they do, Figure 4. Interactions within the CNs system influenced both MCs and EPs systems while simultaneously being shaped by them. In links, CNs were defined by:

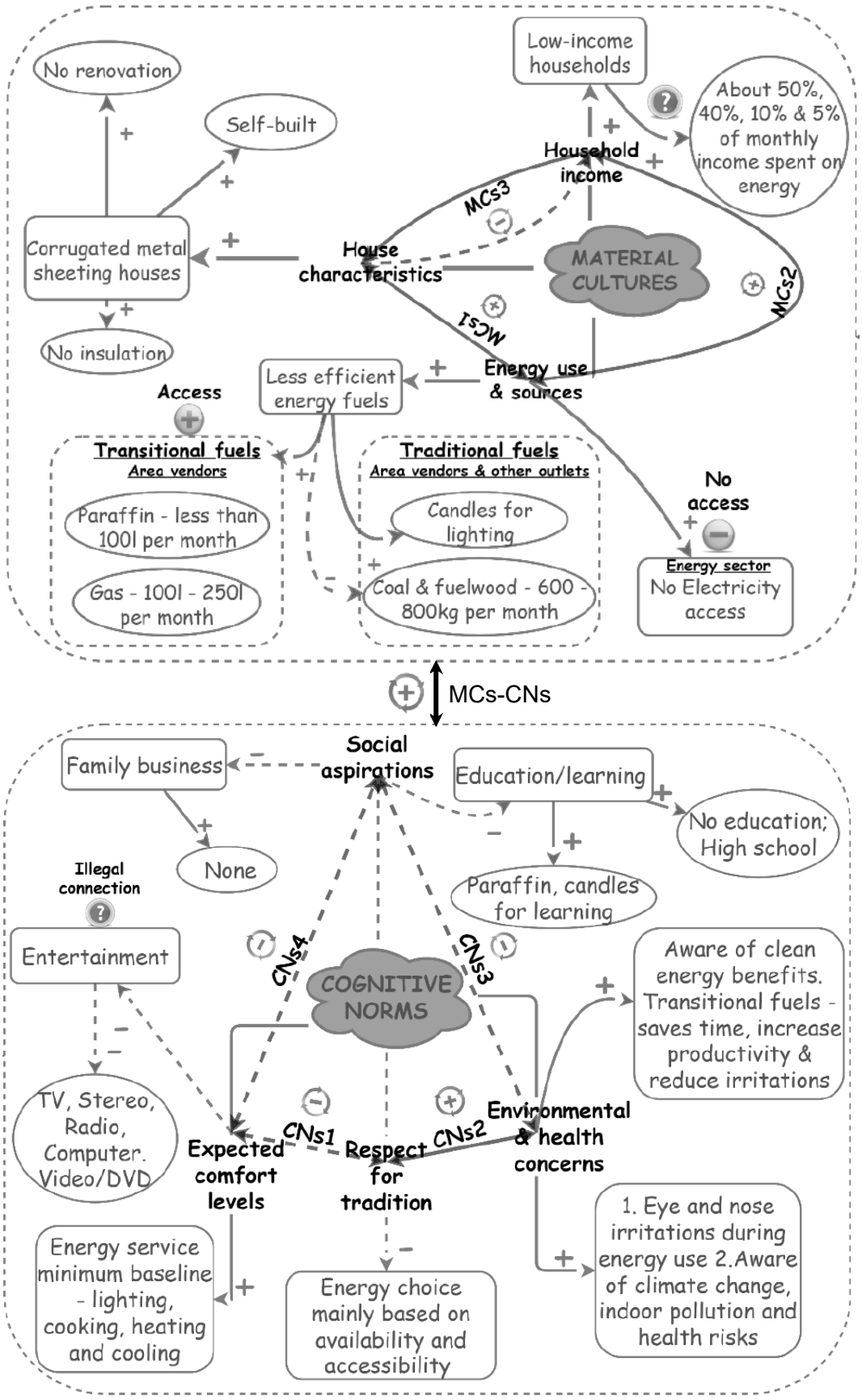

Figure 4. Second Step: Inclusion of CNs CLD design. Causal loops (in black) and links (in grey) are represented in strong (bold lines) and weak (dotted lines) connections, indicating high-level (marked with + signs) and low-level (marked with – signs) system dependency, respectively.

- Meeting the minimum baseline of energy services and entertainment in the form of recorded electrical appliances (which also queried the lack of electricity access in the settlement), although this interaction had low-level system dependency.
- Energy choices were not significantly driven by traditional values but rather by product availability and accessibility and not a strong determinant of system behaviour.
- Awareness of the negative impacts of poor energy use and the benefits of cleaner energy options informed some preferences, albeit weakly.
- Education was limited to high school certificates, using paraffin and candles for learning, and poor socioeconomic activities, such as small family businesses, also contributed weakly to defining system behaviour.

The CNs1 loop highlighted weak interactions between the subsystems, which, in turn, were dependent on CNs3 and CNs4 loop activities, with negative reinforcing patterns observed across all three loops, Figure 4. The CNs2 loop, however, showed a positive pattern, where respect for tradition enormously strengthened environmental and health awareness and vice versa. The combined synergisms between the four loops (CNs1-CNs4) produced positive behaviour toward energy preferences, primarily influenced by the disregard for tradition and heightened environmental and health concerns. These interdependencies further resulted in poor energy productivity, characterized by poor socioeconomic or low entrepreneurial activities, limited education, and an inability to exceed the minimum baseline of energy services.

Causal loops at the MCs – CNs system interfaces revealed reciprocal influences, Figure 4. Fundamental synergisms (not visually illustrated in the figure) defining system behaviour includes:

- MCs – CNs1 loop; weak CNs1 loop activities were strongly impacted by all MCs loops, particularly in querying the possibility of electricity theft in the settlement[39].
- MCs – CNs2 loop; the energy use and sources subsystem (captured in MCs1 and MCs2 loops) strongly impacted CNs2 loop activities.
- MCs – CNs3/CNs4; similar to CNs1 loops, all MCs loop activities strongly influenced CNs3 and CNs4 loops through their linked elements.

ENERGY PRACTICES

In the third step, causal links and loops were included to analyze the interrelationships within the EPs system, Figure 5. This step marked the development of the EPM, tailored to the case study energy poverty analysis. Central to the energy price structure subsystem, EPs were defined in links by:

- Lighting choices – dominated by paraffin and candles, with light bulbs present but not widely used.
- Cooking practices – using mainly paraffin, gas stoves, and fuelwood with minimal use of electric stoves.
- Heating devices – predominantly using paraffin and charcoal heaters, with fewer gas portable units and heat pumps.
- Cooling practices – involving more traditional methods like opening windows and doors with limited use of modern cooling technologies.

The system's four casual loops (EPs1-EPs4 loops) indicated positive reinforcing patterns, strengthening the energy price structure's relationships with other subsystems in shaping behaviour, Figure 5. The loops between the system interfaces demonstrated that EPs' activities were not self-contained but influenced by MCs and CNs' system behaviours. Conversely, EPs had a limited role in shaping behaviours within the CNs system. For instance, using paraffin stoves for cooking (EPs) cannot successfully motivate any aspect of social aspirations (CNs) in households. Key interactions from coupled interfaces (not) visually depicted in the figure are highlighted as follows:

- MCs – EPs loops; all MCs loops influenced the EPs1 strong loop, reinforcing the causal influence between the energy price structure and lighting choices within the EPs system. Similar influences were evident in MCs - EPs2, MCs - EPs3, and MCs - EPs4 loops, suggesting the EPs' strong system dependency on MCs.
- CNs – Eps; all CNs loops strongly impacted all EPs loops, except for the CNs2 – EPs inverse but a weak loop. This inverse weak loop stemmed from CNs2 linked elements (which, in turn, were strongly determined by MCs loops) that showed no impact on mitigating poor energy practices or encouraging the use of the finest appliances in households.

Figure 5 presents the EPM elucidating systems perspective on energy poverty analysis and describing energy poverty situations in the settlement based on significant synergisms within and across the systems (MCs – CNs – EPs), highlighted as follows:

- **Poor energy-use patterns and efficiency (MCs)** in informal households were driven by poor energy use and sources, inadequate housing characteristics, and low household income. These limitations contributed to reliance on local energy devices (EPs), poor social aspirations, the minimum baseline of energy services, and heightened environmental and health concerns (CNs).
- **Poor energy productivity (CNs)** in households rooted in constrained social aspirations, influenced by inefficient energy use and sources, low income (MCs), and dependence on local devices (EPs). While the minimum baseline of energy services was met (which aligned with acceptable standards [1]), energy productivity remains optimal. Furthermore,
  - **Positive behavioural patterns toward energy preferences (CNs)** were reflected in a disregard for tradition and a heightened awareness of environmental and health concerns, as indicated by the CNs2 loop. Despite these positive aspects, the CNs2 loop potential was limited by the solid causal influences flowing within and between the three systems, reinforcing inefficiencies.
- **Local energy appliances and affordable energy prices (EPs)** in the settlement. The availability and accessibility of paraffin and gas (MCs) strengthened the use of local devices and the affordability of local energy products (EPs). In addition, reliance on less efficient fuels and the lack of electricity access (MCs) perpetuated poor energy practices (EPs) despite awareness of environmental and health concerns (CNs).

INSIGHTS AND POLICY IMPLICATIONS

The synergistic analyses revealed that inefficiencies in MCs directly impacted CNs and EPs, collectively contributing to the overall poor model performance, highlighting the need for targeted solutions addressing structural barriers (e.g., housing conditions, income disparities), behavioural shifts (e.g., improving energy preferences), and accessibility to cleaner energy sources while fostering collaborative and integrated policy approaches. These analyses effectively identified system elements that exponentially drive energy poverty and enable sustainable energy access (SEA). For instance, the energy use and sources subsystem was pivotal in meeting the baseline of energy services, poor energy productivity, and the widespread use of local energy devices in the target settlement. These outcomes show consistency with the literature on informal settlements in South Africa [3, 24]. However, despite these limitations, this subsystem harbors integral elements capable of catalyzing transitions toward clean energy access, improved energy productivity, and affordable energy practices in target settlement.

The EPM further revealed no laid-out procedure for mitigating energy poverty in any local settings [40]. For example, households utilized less efficient fuels (MCs) and only met the essential energy services (CNs) while continuing to use local energy devices (EPs). Another instance is that household low-income status (MCs) indirectly influenced the energy price

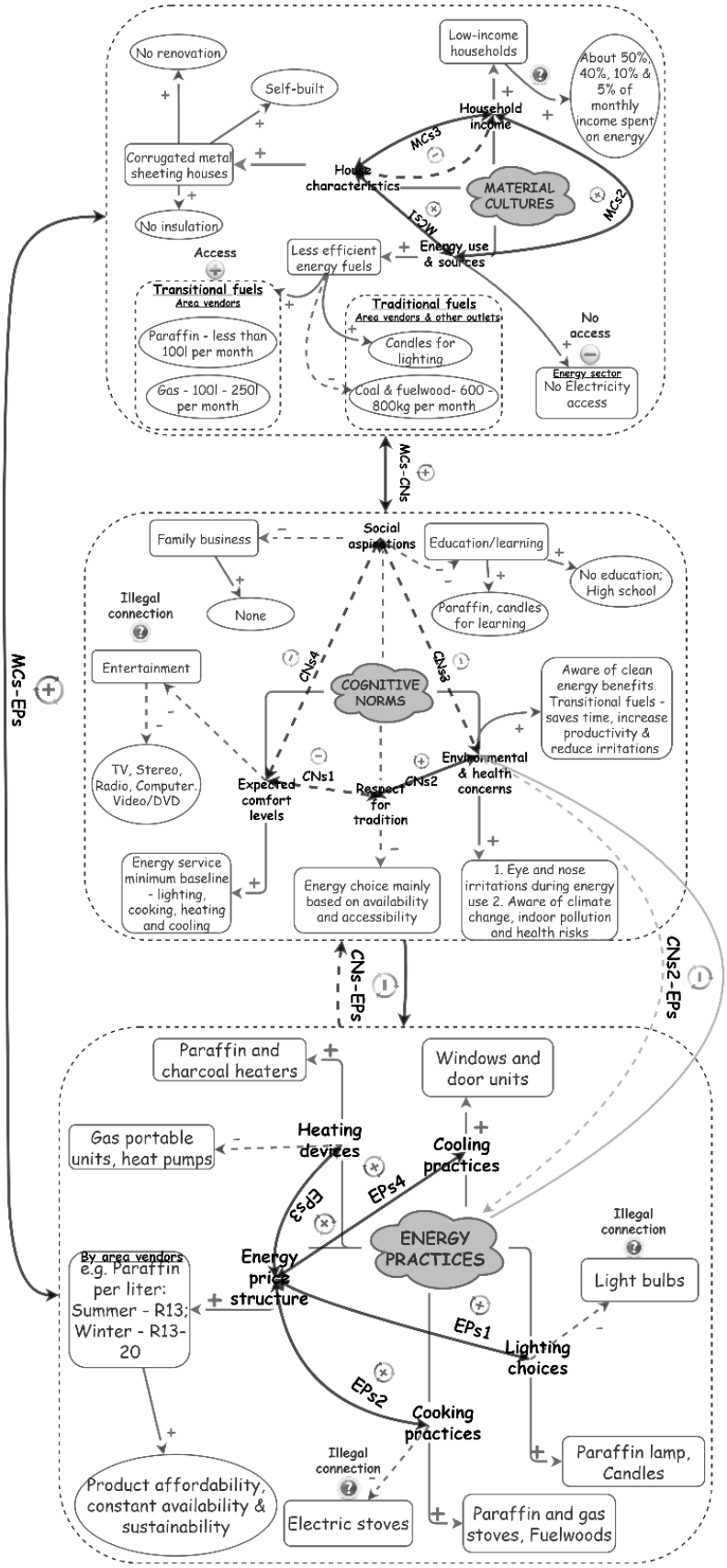

Figure 5. Third step: The EPM development. Inclusion of EPs CLD. Causal loops (in black) and links (in grey) are represented in strong (bold lines) and weak (dotted lines) connections, indicating high-level (+ sign) and low-level (– sign) system dependency, respectively.

influenced structure to be affordable (EPs), although it limits education and social aspirations (CNs). These highlight the system interconnectedness, where interventions in one element inadvertently trigger counterproductive influences in another, diminishing the practicality of policy initiatives or interventions. Instead of implementing actions that narrowly target a single element, such as workshops to promote positive behaviour without addressing the foundational energy-use patterns (MCs), the model reveals the importance of identifying actionable elements within the systems with multiple exponential impacts. For instance, providing access to electricity or cleaner energy options (such as renewables or transitional fuels like paraffin) displaces traditional fuels like charcoal, significantly improving energy-use patterns and efficiency (MCs), as well as energy preferences and productivity (CNs) in informal households. As another instance, promoting local entrepreneurial activities (CNs) can directly elevate household low incomes (MCs) to support better energy practices (EPs).

The common assumption in energy access programs is that households readily adopt a new energy technology once provided, disregarding factors acting singly or in groups that oppose such immediate adoption in a given place and time [41]. However, the model showed the intricate interactions among system elements that could initiate delayed technology use in an energy-poor community. For instance, even with future access to electricity (MCs), adoption delays are likely due to low-income status (MCs) exacerbated by electricity price hypes [3] limiting affordability and persistent reliance on less efficient energy products influenced by their immediate availability and accessibility in the target settlement. The institutional landscape is critical in enabling new technology use and should employ a multifaceted approach involving community stakeholders to address system interactions and barriers more proficiently. In contexts like the case study area, institutional challenges, such as delays in grid electrification, often hinder energy access progress. However, stakeholder-driven initiatives can bridge gaps by promoting free and subsidized transitional fuels (see Table 1) to displace traditional fuels, such as charcoal and fuelwood, reducing health risks from harmful emissions and enhancing productivity (CNs) while building capacity for future clean energy adoption. These strategies address immediate energy needs and create pathways for sustainable energy transitions, fostering social acceptance and long-term adoption of clean energy technologies. Once again, stimulating aspects of one system may be less effective in producing change than stimulating another, with more significant influences on elements within and between the system interfaces. For instance, promoting educational and entrepreneurial opportunities (CNs) can shift household behaviour and perceptions, increasing openness to adopting new energy technologies once provided in the study area.

The energy access process frequently faces constraints when the target group's needs and strengths are not adequately identified or addressed [42]. The model provides the platform to help planners understand current conditions and design effective, context-sensitive external interventions. Regrettably, sociotechnical decisions in energy access plans are made without sufficient input from the target communities. Nonetheless, much attention should be focused on addressing energy poverty based on the context of a place and responses generated when designing solutions pertinent to that place. This can be achieved by holistically viewing the interactions of MCs, CNs, and EPs in conditioning certain elements from opposing sustainability and, ultimately, promoting a willingness to a behaviour change. There are certain conditions where CNs, for example, are favourable but are compromised by inefficient MCs or another situation where CNs favour MCs but are weakened by poor EPs. Addressing these systems' lop-sided components through appropriate interventions while targeting a place's socioeconomic and cultural settings can conveniently improve situations. Besides, resolving the problem systems may require revoking some causal influences to motivate interventions. Essentially, the prime understanding of elements prolonging the system problems can lead to developing context-sensitive interventions and policy strategies.

The success of system synergies in invoking the right solutions relies on the robustness of existing policies [43-46]. Policies addressing MCs' elements have cascading effects, improving CNs, EPs, and overall model performance [43-46]. However, the simultaneous resolution of all problem systems remains challenging due to the limitations of current policy frameworks. At the time of this study, policy challenges exacerbated energy poverty in the target settlement [2, 47, 48]. These challenges included a focus on addressing energy inequality and supply shortages in the broader energy sector, often overlooking the nuanced realities of informal settlements [2, 48]. Such settlements are typically neglected in initial energy access planning due to their architectural volatility and lack of standardized infrastructure. These communities are often disproportionately linked to energy poverty without sufficient consideration of how policies could propel household-level sustainability. New place-based policy strategies should promote energy-use techniques at the household level through better technologies and practices. Alternative energy access options, such as renewable energy and localized microgrids, must be explored to sustainably balance demand and supply factions. Encouraging input from affected communities and relevant organizations further guarantees policies align with local needs and realities. Given that the EPM platform identifies the root causes of energy poverty grounded in the target group's specific conditions and resources, policymakers can design solutions that directly address energy inequality while avoiding unsustainable mitigation efforts. The model insights generate a worthy rotation motivating cross-sectoral collaboration to ensure that policy initiatives align with broader social, economic, and environmental goals. By leveraging these model insights, policymakers can circumvent the traditional exclusion of informal settlements from energy planning, bridging the gap between high-level policy intentions and on-the-ground realities and fostering resilience and inclusivity in energy access planning schemes. On balance, the model can promote policy cohesiveness and design of tailored interventions, promoting SEA in informal settlements at large in South Africa.

CONCLUSIONS AND LIMITATIONS

Energy-related issues in informal settlements [22, 24] and other similar communities [20, 21] have been widely documented, but none have been formalized in the field of SsT. The author adopted SsT to present a different but cohesive outlook on the complexities of energy poverty dynamics in informal settings. CLDs, synced with SsT and built into the EPM, have been shown to allow the integration of diverse elements into broader system configurations. The model utility generated multiple spectra of outcomes, facilitating the understanding of synergistic interactions and identifying critical gaps and required assets within the problem systems. The model further validated the synchronicity of actions necessary to address energy poverty problems, substantiating the potential of existing policies and initiatives to mitigate situations. However, policy support must be carefully scrutinized, and with a broad vision, several EPM insights must be considered. While these insights are promising, policymakers must remain adaptive, recognizing that the distinct characteristics of target communities require flexible and multidimensional approaches.

Despite its robustness, the model may display complexity when addressing energy poverty situations in a case-to-case scenario. Introducing new elements or accounting for unknown factors may generate varied responses, potentially complicating understanding the problem systems. This limitation is not unique but reflects the inherent complexity of any societal design. Emerging factors such as disruptive technologies, sociocultural changes, or collective traits of target groups may influence the model's outcomes. Future iterations of the model should recognize and incorporate the impacts of disruptive technologies, gradual societal changes, or new causal influences, such as grid electricity access or improved supply chain competence. These adaptations will not fundamentally alter the model but enhance its inclusivity and precision to enable effective interventions, ensuring its continued relevance and effectiveness in diverse settings.

APPENDIX

Table 1. Empirical observations of sampled parameters/elements in distinctive EPSs in the case study area.

Category	Parameters/Elements (*n* – Number of respondents)
Dwelling Types and Household Sizes	**a)** Dwellings (n = 117) are mainly shacks, built with corrugated metal sheeting (98,51 %); Mobile homes (1,49 %) ✓ Self-built (83 %) dwellings (n = 114); built by the local authority (26 %). ✓ Non-insulated (n = 77); poorly insulated (n = 19). ✓ Not renovated (63 %) dwellings (n = 120); unsure of renovating (5 %); renovated (31 %).
	b) Household sizes range from one to nine; with at least one member over 18 years (n = 101).
Electricity Access and Energy Use	**c)** Households (n = 96) indicate no electricity access (95,83 %); Few indicate access (4 %) ✓ Primary energy use is paraffin - for lighting (46 %, n = 186); cooking (66 %, n = 139); and heating (59 %, n = 128) ✓ Followed by candles (40%) for lighting; gas (14 %) and fuelwood (12 %) for cooking; and fuelwood (18 %) and coal (14 %) for heating
	d) Energy (paraffin) preferences (n = 117); are due to affordability (52,14 %), accessibility and availability (36,75 %); convenience (7.69%); environmentally friendly (2,56 %); and respect for tradition (0,85 %)
	e) Households (n = 97) obtain paraffin and gas from the area vendors; fuelwood and charcoal obtain from woodlots and other outlets (n = 7).
	f) For space heating, households use paraffin (about 40 %; n = 67), charcoal heaters (39 %); electric portable (4 %) and gas portable units (10 %); heat pumps (6 %).
	g) Traditional incandescent and LED light bulbs (n = 39); and some electrical appliances (n = 84) are recorded
	h) For space cooling, windows and door units (97 %; n = 71); and electric fans and evaporative coolers (3 %).
Energy costs on household income	**i)** Households (n = 127) mainly use less than 100 *l* (n = 34), 100-250 *l* (n = 17), and more than 250 *l* (n = 12) of paraffin in winter (n = 64) than in summer (n = 63). **j)** Gas consumption rates decline from summer (n = 13) to winter (n = 8); fuelwood and coal rates increase across seasons.
	k) One-third of households (n = 78) have energy costs of 0,5 of household income, monthly; others have 0,4 (17%), 0,2 (4%), 0,1 (15%), and less than 0,05 (23%). **l)** Most household sizes (n = 99) spend less than R300 (50 %) and R301-R999 (41 %) on energy products
Energy Productivity and Expected Energy Benefits	**m)** About future energy price hype, among n = 100 households: 83,33 % worry a lot; 3,92 % worry a fair amount; 1,96 % do not very much and 10,78 % do not worry at all. **n)** About the impact of using less efficient fuels on the climate, households (n = 104) worry: a lot – 90,57 %; a fair amount – 2,83 %; not very much – 2,83 %; not at all – 3,77 %. **o)** Households (n = 96) have eye and nose irritations using energy products as follows: ✓ when using (n = 40): very much – 80,00 %; not too much – 17,50 %; not at all – 2,50 %. ✓ immediately after using (n = 36): very much – 86,00 %; not too much – 13,89 %; not at all – 0,00 %. ✓ a long time after using (n = 20): very much – 85,00 %; not too much – 5,00 %; not at all – 10,00 %. **p)** Households (n = 110) visit a hospital or clinic one or two times a month (~ 35 %); others (~ 47 %) have zero visits. **q)** Households (n = 100) have no kind of family business (~ 93 %); others (~ 5 %) run businesses such as fashion, food vending, and hair salons **r)** Households (n = 98) have at least one member with a high school certificate (68 %); no education (22 %); a diploma (6 %); and degree certificates (3 %). **s)** For improved energy use, households (n = 104) suggest solar PV (n = 7) [43]; external (n =17) and internal thermal insulation (n = 14); replacement of windows, doors (n = 18), and roofs (n = 24); pre-paid meter installations (n = 24) [46]; free delivery of paraffin [45] and Reconstruction and Development Programme (RDP) houses [48].
Local Energy Supply and Sustainability	**t)** Two area vendors – one sells 1 *l* of paraffin at R13 in summer and R13-R20 in winter; the other sells 5 kg of gas for R120 and 9 kg for R220 regardless of seasonality. **u)** Both vendors confirmed product affordability, availability, and sustainability, except in a few winters when demand is high.

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FINANCIAL IMPACTS OF THE CARBON BORDER ADJUSTMENT MECHANISM ON SELECTED TRADE PARTNERS: CROSS-NATIONAL AND CROSS-SECTORAL ANALYSIS

Emira Kozarević, Mirnesa Baraković Nurikić and Muhamed Ibrić*

University of Tuzla, Faculty of Economics
Tuzla, Bosnia and Herzegovina

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ABSTRACT

The Carbon Border Adjustment Mechanism (CBAM) is an import fee levied by a region, i.e., the European Union (EU), that taxes carbon on goods produced in countries that do not tax carbon. This EU climate neutrality support mechanism, which should be implemented by 2050, has caused some concerns. For example, it could reduce the export of the EU's trading partners, especially those countries largely dependent on exporting energy-intensive goods and materials to the EU. Least developed countries, due to their high risk of vulnerability and high exposure, could face particularly pronounced adverse effects from the CBAM's introduction. Therefore, this article aims to analyze how the introduction of the CBAM will affect the EU's external trade partners, with particular attention to its potential consequences for selected economies. Most of the literature related to the introduction of the CBAM focuses on the consequences for EU countries. However, this mechanism, which aims to decrease CO2 emissions and encourage a low-carbon transition, could disproportionately affect some countries outside the EU. That is why the article uses data on the exposure of selected non-EU countries to the CBAM, utilizing data on the export of the CBAM-affected products to the EU and CO2 emission intensity. The analysis encompasses five regions and 59 countries, using data from the year 2019. The rationale for using 2019 data is to avoid the effects of global shocks in recent years, such as the coronavirus pandemic and Russia's invasion of Ukraine. The analysis results reveal that the exposure of regions and countries varies based on the strength on their trade relations with the EU, leading to different trade impacts from the CBAM. The lowest exposure is observed in the regions of the Americas and Australia. This article provides valuable insights to policymakers and entrepreneurs in navigating the challenges and opportunities arising from the interlinkage of environmental policies and global trade dynamism. It can help facilitate decision-making related to participation in foreign trade involving products with a higher carbon emissions.

KEY WORDS

CBAM, financial impacts, relative CBAM exposure index, trade relations

CLASSIFICATION

JEL: F18, F38, H23, Q56, Q58

*Corresponding author, η: muhamed.ibric@untz.ba; +387 60 3415471;
Faculty of Economics, University of Tuzla, Urfeta Vejzagića 8, 75 000 Tuzla, Bosnia and Herzegovina

INTRODUCTION

The EU Emissions Trading System (ETS) certainly affects the costs incurred by the manufacturers in the EU, and consequently, their competitiveness in both EU and international markets. It can be foreseen that EU manufacturers would react to such a system in various ways, depending on product characteristics such as carbon-intensiveness and trade volumes [1]. The EU faces two main challenges related to this situation. One is the potential loss of employment and production to other countries, driven by adherence to CO_2 emission regulations. Additionally, any producer unwilling to comply with CO_2 emission reduction regulations could realocate their business outside the EU, continuing production with the same emission level as before. Ultimately, this would mean that efforts to reduce CO_2 emissions and create a greenhouse within the EU would have limited impact and could not be effectively applied on a global scale.

The threat of carbon leakage is an issue that arises from the disparity between regions or countries that do or do not implement effective carbon regulations. In the context of reducing CO_2 emissions, one of the most important strategic decisions could be the adjustment of the CBAM. The primary purpose and goal of this mechanism is to eliminate differences in carbon costs in traded goods through border adjustment procedures [1]. The CBAM aims to reduce and prevent carbon emissions while placing foreign producers on equal footing with EU producers, who are required to comply with the EU ETS regulations. This would create a level playing field for producers both within and outside the EU. Additionally, the CBAM could encourage non-EU governments to adopt greener policies and motivate their producers to reduce their carbon emissions [2].

A United Nations Conference on Trade and Development study [3] found that the CBAM could alter trade patterns by favoring economies with relatively carbon-efficient production and suppressing exports from developing economies with carbon-intensive industries. Economies with emissions-intensive and trade-exposed products as a large share of their exports would be particularly vulnerable. Moreover, the risks associated with adapting to the CBAM would increase for economies that rely heavily on the EU as their export market, as well as for those lacking the capacity to monitor and report production-related carbon emissions [4]. Economies struggling to adapt to the low-carbon paradigm may face greater risks, due to their exposure and vulnerability to the CBAM.

The CBAM's introduction can have significant economic implications for trade and investment, particularly in developing countries. Building on this, the following paragraph provides insight into the research question addressed by this article and outlines its research aim.

The research question is:

> **RQ:** *Are there significant differences in exposure to the CBAM among selected non-EU countries?*

The aim of this research is to conduct a comparative analysis of the exposure of selected non-EU countries to the CBAM, both in aggregate and by sector.

The article is structured as follows. Section 1 provides a literature review. Section 2 outlines the context of the research. The third part presents the data used and the methodology. Section 4 illustrates the findings and discusses the results. Section 5 concludes the article and proposes directions for future research.

LITERATURE REVIEW

The introduction of the CBAM has triggered a lively debate on its potential impacts, particularly when it comes to developing countries [5] Many authors [6-11] review environmental policy design features such as the CBAM. From an economic perspective, the

most pressing concern in studies of the CBAM is its effectiveness in promoting fair competition, curbing carbon leakage, and improving global welfare [5]. Depending on how the impacts develop, the CBAM's effects can be classified as direct and indirect. The direct effects are, in fact, variations in market outcomes caused by (relative) price changes due to CBAM implementation, such as reducing competitiveness loss and carbon leakage triggered by unilateral climate policies [12, 13]. Indirect effects refer to the CBAM acting as a threat that motivates countries to enhance their climate ambitions, either by inducing economies to join the climate club or by promoting more stringent carbon policies.

The notion that the CBAM can influence affected countries to adopt emission controls of their own is also referred to as its strategic value [5]. Böhringer et al. [14] find that the CBAM can effectively mitigate carbon leakage and smooth out the negative impacts on energy-intensive and trade-exposed sectors in countries with unilateral carbon pricing mechanisms. In an extensive literature review by Newman [15], the CBAM is frequently advocated as an effective, WTO-compliant, non-discriminatory tariff, and a precautionary measure. According to the "pollution haven hypothesis" or the "pollution haven effect," as countries become economically wealthier, they tend to introduce stringent environmental regulations that force domestic firms to outsource or relocate polluting industries to regions with less strict environmental rules [16]. Concerns have been raised about the ecological inequality that low-income economies likely face from increased pollution and environmental degradation due to hosting these relocated industries [17].

As noted by [16], the CBAM is one of the practical instruments a country can employ to address carbon leakage and the competitiveness of domestic industries in the local market. The key idea behind the CBAM is to impose a carbon price on imported goods based on carbon content to create a level playing field with domestically produced products. Many economists prefer the CBAM proposal and argue that it is feasible, legal, and has the potential for a significant impact on global emissions. There is a consensus among many economists that the CBAM is legal under WTO laws and guidelines.

Before it came into force, several studies, including those of [3] and [18], indicated that economies relying on exporting goods with high carbon content to the EU27 would be adversely affected. Thus, the impact of the CBAM is a subject of significant interest and debate among policymakers, economists, and global stakeholders [14, 16, 19-21]. Numerous authors believe that the introduction of the CBAM will hurt poorer countries due to their low level of energy transition. Studies like that of [3] suggest an increased diffusion and uptake of environmentally friendly technologies.

A study by [22] finds that the impact of the carbon tax on most trading partners of the EU27 will be limited, but the effect will also vary widely among regions and sectors. In a review of the impact of the intended carbon tax by the EU, [3] finds that EU-CBAM has the potential to alter global trade patterns in favor of countries with less carbon-intensive production processes. This impact suggests that the exports of developing countries to the EU27 will be adversely affected. [15] argues that a carbon border tax is likely to succeed in reducing carbon emissions if regulated and enforced properly.

Previous literature largely analyzes the effects of the CBAM on EU member states, focusing on the potential reduction in imports into the EU and the increase in the price of imported goods. Consequently, there is a lack of studies providing a comparative analysis of the effects of the CBAM on countries outside the EU that have trade relations with the EU.

This article addresses the aforementioned literature gap by providing a comprehensive comparative analysis of the exposure of EU trade partner countries, detailing the country-specific contexts, and linking them to the exposure to the CBAM. The analysis is conducted for each sector covered by the CBAM measure.

BACKGROUND

CONTEXTUAL OVERVIEW

As countries begin to price carbon and implement additional policies to address environmental damage, the issue of "carbon leakage" has emerged. Instead of reducing pollution as intended, domestically produced products are beign replaced with more carbon-intensive imports. This undermines the effectiveness of carbon pricing and makes environmental regulations less effective. To combat this, the European Commission proposed the CBAM on July 14, 2021. This carbon border tax aims to prevent carbon leakage and increase global accountability for environmental degradation by equalizing the price of carbon in the EU with that of imports [15]. The CBAM functions as a tax based on the carbon content of imported goods and the price difference between carbon in the EU and the exporting economy, where a carbon price is often nonexistent [4].

IMPLEMENTATION TIMELINE OF THE CBAM

Figure 1 presents a timeline of the CBAM's introduction. As illustrated, in December 2019, the European Commission adopted a communication on the European Green Deal. This was followed by the "Fit for 55" communication in July 2021, which included a package of legislative proposals aimed at achieving a 55 % reduction in greenhouse gas (GHG) emissions by 2030, as an intermediate goal towards climate neutrality by 2050 [2]. The package also included a proposal for implementing the CBAM [23].

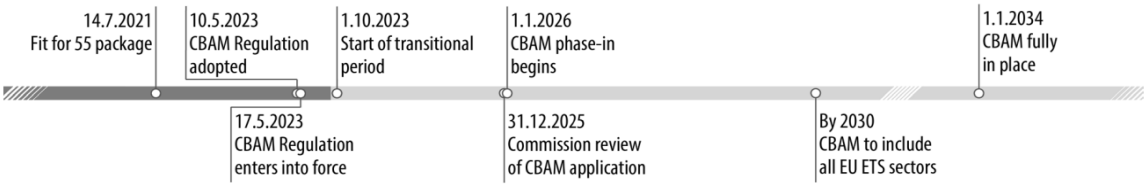

Figure 1. CBAM's introduction timeline

In May 2023, the EU adopted Regulation 2023/956, which establishes the CBAM to impose a price on GHG emissions from imports equivalent to that of products manufactured in the EU. By adopting the CBAM, the EU became the first jurisdiction to extend its domestic carbon price to emissions generated outside its borders [24].

OVERVIEW OF ACTORS IN THE CBAM

The CBAM aims to strengthen climate action by including imported goods in carbon pricing, thereby giving goods with a lower carbon footprint an advantage over those associated with high emissions. The CBAM ensures that the same carbon price is paid for goods within the EU, irrespective of whether they are produced in the EU and thus covered by the EU ETS or abroad. Importers must report the emissions occurring during production (embedded emissions) and surrender CBAM certificates, which are sold at the average price of EU allowances. If producers in third countries pay a carbon price, the surrender obligation is reduced to reflect the price effectively paid, Figure 2.

OVERVIEW OF CBAM SECTORS, REPORTING REQUIREMENTS AND CERTIFICATE PRICING

The sectors covered by the CBAM are cement, electricity, fertilizers, iron and steel, and aluminum, as well as some precursors and downstream products derived from cement, iron and steel, and aluminum. The CBAM's product scope is expected to be extended to cover all EU ETS sectors by 2030. The CBAM also includes indirect emissions from the generation of

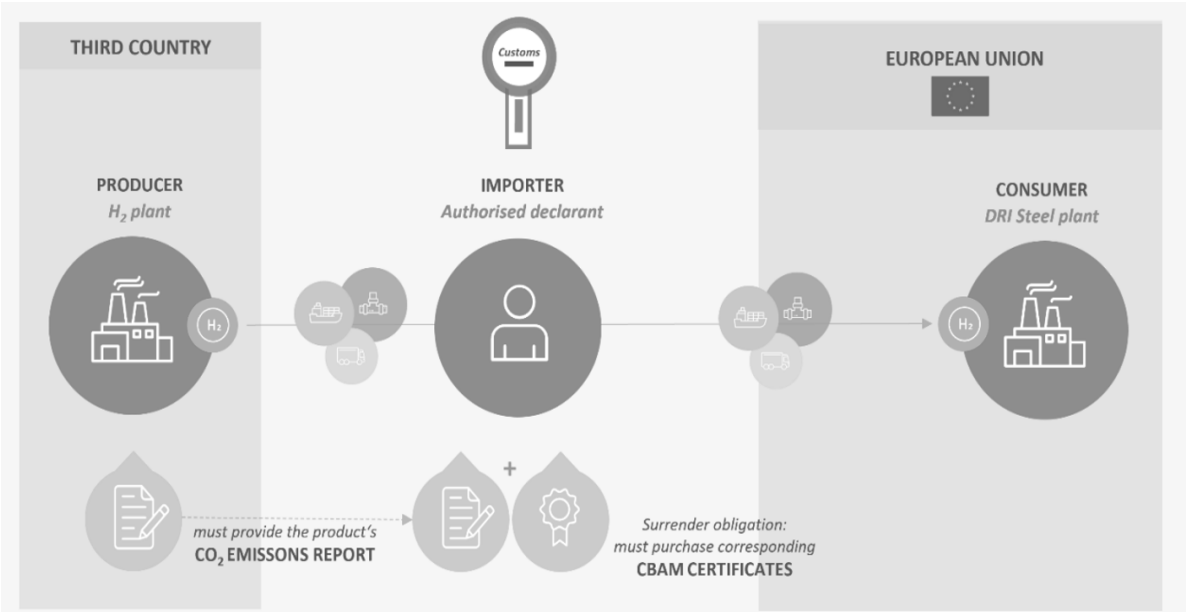

Figure 2. Participants involved in the CBAM and their roles.

electricity used for producing goods, except for goods for which the EU ETS Directive allows the member states to compensate indirect costs [2]. The GHG emissions covered under the CBAM are CO_2 and, where relevant, nitrous oxide (N_2O) and perfluorocarbons (PFCs) [25]. Table 1 provides an overview of the emission requirements related to the sectors subject to CBAM.

Table 1. Overview of emission-related requirements for CBAM sectors.

Issues	CBAM goods					
	Cement	**Fertilisers**	**Iron/Steel**	**Aluminum**	**Hydrogen**	**Electricity**
Reporting metrics	(per) Ton of goods					(per) MWh
GHG covered	Only CO_2	CO_2 (plus N_2O for some fertiliser goods)	Only CO_2	CO_2 (plus PFCs for some aluminum goods)	Only CO_2	Only CO_2
Emission coverage during transitional period	Direct and indirect					Only direct
Emission coverage during definitive period	Direct and indirect		Only direct, subject to review			Only direct
Determination of direct embedded emissions	Based on actual emissions, but estimations (includings default values) can be used for up to 100 % of the specific direct embedded emissions for imports until 30 June 2024 (i.e., CBAM reports due until July 31, 2024) and for up to 20 % of the total specific embedded emissions for imports until December 31, 2025.					Based default values, unless several cumulative conditions are met
Determination of indirect embedded emissions	Based on actual electricity consuption and default emission factor for electricity, unless conditions are met (i.e., direct tehnical connection or power purchase agreement). Estimations (including default values) can be used for up to 100 % of the specific indirect embedded emissions for imports until June 30, 2024.					Not applicable

During the transitional period (i.e., from October 1, 2023, to December 31, 2025), only reporting requirements are in place. Starting January 1, 2026, importers will be required to acquire CBAM certificates for the GHG emissions associated with the production of imported goods that are not subject to equivalent carbon pricing in the country of origin [2]. The penalty for non-compliance is a charge ranging from EUR 10 to EUR 50 per ton of unreported emissions.

The price of the CBAM certificates follows the price of emissions allowances in the EU ETS, thereby creating a level playing field between foreign and EU producers. The CBAM will gradually replace the EU ETS free emissions allowances mechanism, utilizing a 9-year phase-out of free allowances under the EU ETS from 2026 to 2034, with a corresponding phase-in of the CBAM. During this period, free emissions allowances will be reduced at an initially slower rate, which will accelerate as the period ends. The reduction rate for free allowances, according to the EU ETS, is as follows: 2,5 % (2026); 5 % (2027); 10 % (2028); 22,5 % (2029); 48,5 % (2030); 61 % (2031); 73,5 % (2032); 86 % (2033); and 100 % (2034) [2].

RESEARCH METHODOLOGY

This study uses descriptive statistics to analyze the exposure of selected non-EU countries to the CBAM, utilizing data on carbon emission intensity and the export of CBAM-affected products to the EU. The authors employ methods of analysis and deduction to interpret the collected data, ensuring a thorough examination of the exposure and challenges.

The analysis includes five regions and 59 countries for which data for the year 2019 were available on the World Bank website, along with two additional countries – Norway and Switzerland) – that are included only in the sector-specific exposure analysis. The rationale for using 2019 data is to avoid the effects of recent global shocks, such as the coronavirus pandemic and invasion of Ukraine, as noted in [26]. This is shown in Table 2.

For the comparative analysis of exposure for each country, both aggregate and by sector, the Relative CBAM Exposure Index developed by the World Bank is used, as stated by [4]. The Relative CBAM Exposure Index is designed to identify countries with high exposure to the CBAM, using carbon emissions intensity and exports of CBAM-affected products to the EU. Assuming a carbon price of USD 100 per metric ton, the index measures the additional cost of CBAM certificates for exporters compared to the average EU producer, adjusted by the proportion of exports to the EU market. It recognizes cost changes in the EU market, where EU producers also bear emissions costs, enabling relatively clean exporters to gain competitiveness despite the requirement to purchase certificates. The aggregate relative index represents the trade-weighted relative exposure across all CBAM-affected products [26].

The methodology for calculating the Relative CBAM Exposure Index can be summarized in the following formula:

$$\text{Relative CBAM Exposure Index} = \frac{X_{cs}^{EU}}{X_{cs}^{World}} * \text{USD 100 per ton} * EI_{cs} \quad (1)$$

where c denotes country, s – sector, X – exports, and EI – emission intensity.

This article examines how the selected countries, which are trade partners of the EU, differ in terms of the exposure to the CBAM, both aggregate and by sector. This analysis will identify the countries currently most exposed to additional costs due to the CBAM's introduction.

Table 3 summarizes all variables used in the research, detailing their basic characteristics such as variable name, scope, measurement method, unit of measurement, and source.

Table 2. A list of the selected economies. The categorization of countries by region is based on the division provided in [27]. It has been adapted so that the Americas are considered as one region (without separate division for North America and South America), and Australia and Oceania are combined into a single region (referred to as "Australia" in the following text).

World regions	Country	World regions	Country
Asia	Azerbaijan	Africa	Cameroon
	Bahrain		Egypt
	Cambodia		Ghana
	China		Mauritius
	Georgia		Morocco
	Hong Kong SAR		Mozambique
	India		Senegal
	Indonesia		South Africa
	Iran		Tunisia
	Israel		Zimbabwe
	Japan	America	Argentina
	Jordan		Brazil
	Kazakhstan		Canada
	Kuwait		Chile
	Malaysia		Colombia
	Oman		Costa Rica
	Pakistan		Mexico
	Philippines		Peru
	Qatar		Trinidad and Tobago
	Saudi Arabia		United States
	Singapore		Venezuela
	South Korea	Australia and Oceania	Australia
	Sri Lanka		New Zealand
	Taiwan	Europe	Albania
	Tajikistan		Belarus
	Thailand		Norway
	Turkey		Russian Federation
	United Arab Emirates		Switzerland
	Vietnam		Ukraine
			United Kingdom

Table 3. Overview of key variables in the study**.** The Relative CBAM Exposure Index is based on the following factors: CO_2 emissions intensity of exports (kg CO_2 eq./USD) above EU average intensity, exports to EU (% of country's total exports), and carbon price at USD 100 per ton CO_2 eq. Source: World Bank.

Variable name	Scope	Measurement method and unit measurement
CBAM-affected Products Exports to the EU	Aggregate	% of total CBAM-affected products exports to world % of GDP
	Iron and steel	% of total iron and steel exports to the world
	Fertilizer	% of total fertilizer exports to the world
	Cement	% of total cement exports
	Aluminum	% of total aluminum exports to the world
Relative CBAM Exposure Index	Aggregate	The exporter's emission intensity multiplied by a carbon price of USD 100 per ton
	Iron and steel	The exporter's emission intensity multiplied by a carbon price of USD 100 per ton
	Fertilizer	The exporter's emission intensity multiplied by a carbon price of USD 100 per ton
	Cement	The exporter's emission intensity multiplied by a carbon price of USD 100 per ton
	Aluminum	The exporter's emission intensity multiplied by a carbon price of USD 100 per ton

RESULTS AND DISCUSSION

CBAM EXPOSURE OF SELECTED ECONOMIES: CROSS-NATIONAL ANALYSIS

From Figure 3, it can be seen that the countries closer to the EU have the highest aggregate relative CBAM Exposure Index, indicating higher foreign trade volumes with the EU. These primarily include certain countries in Europe and Asia. Additionally, some countries exhibit a negative value for the exposure index, suggesting that their CO_2 emission intensity is lower than the EU average. Most of these countries are from the Americas (specifically, the South American region).

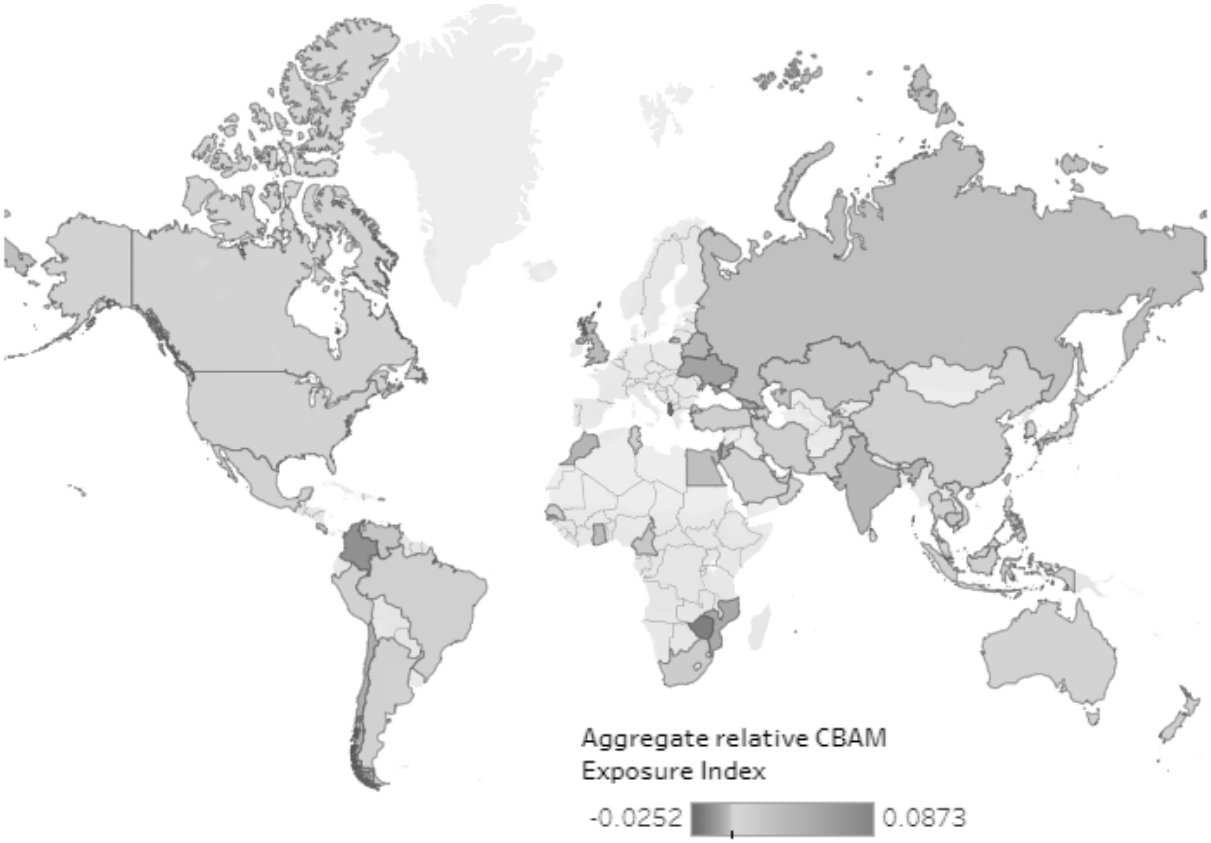

Figure 3. Aggregate Relative CBAM Exposure Index values for the observed regions.

In the rest of the article, the basic trends related to the introduction of the CBAM in the selected countries are explained. It involves an analysis of CBAM-affected product exports to the EU as a percentage of total CBAM-affected product exports to the world, CBAM-affected product exports to the EU as a percentage of GDP, and the values of the total Relative CBAM Exposure Index for the analyzed countries.

Figure 4 illustrates that CBAM product exporters to the EU, as a share of their total CBAM-affected products exported to the world, are predominantly from Africa; more specifically Cameroon (93,4 %), Zimbabwe (87 %), and Mozambique (73,7 %). European countries follow, with the United Kingdom (68,9 %), Albania (58,7 %), and Belarus (50,2 %). Among the smallest exporters of CBAM-affected products to the EU are countries from the American region, such as Senegal (1,1 %) and Costa Rica (0,9 %), as well as countries from Asia, including Singapore (1 %) and Qatar (0,8 %).

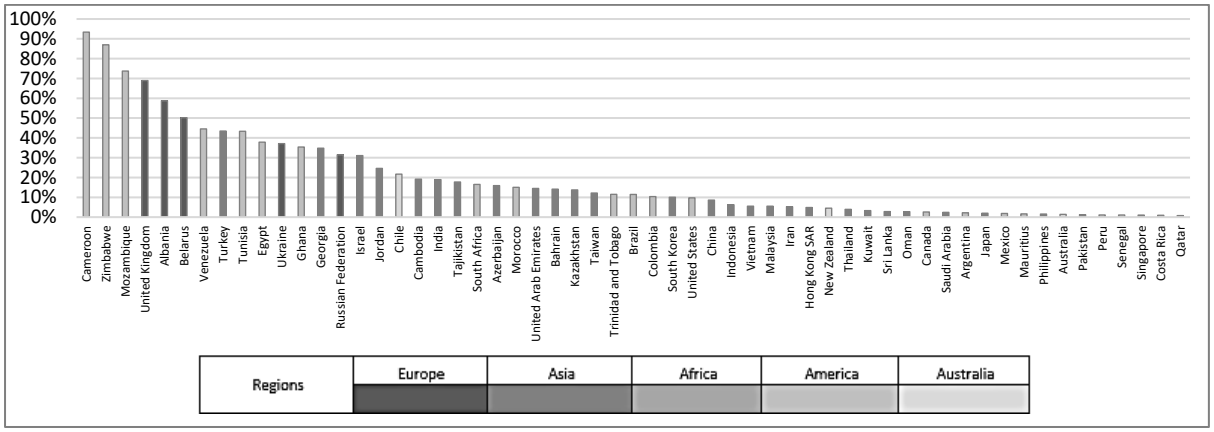

Figure 4. CBAM-affected product exports to the EU (% of total CBAM-affected product exports to the world).

Figure 5 shows the export of CBAM-affected products to the EU as a percentage of GDP. The graph excludes countries with a CBAM value as a percentage of GDP of zero. The largest exporter of CBAM-affected products relative to GDP is Mozambique (6,9 %), followed by Ukraine (2,4 %) and Belarus (1,4 %). It is noteworthy that for most of the observed countries, the export of CBAM-affected products as a share of GDP is not economically significant.

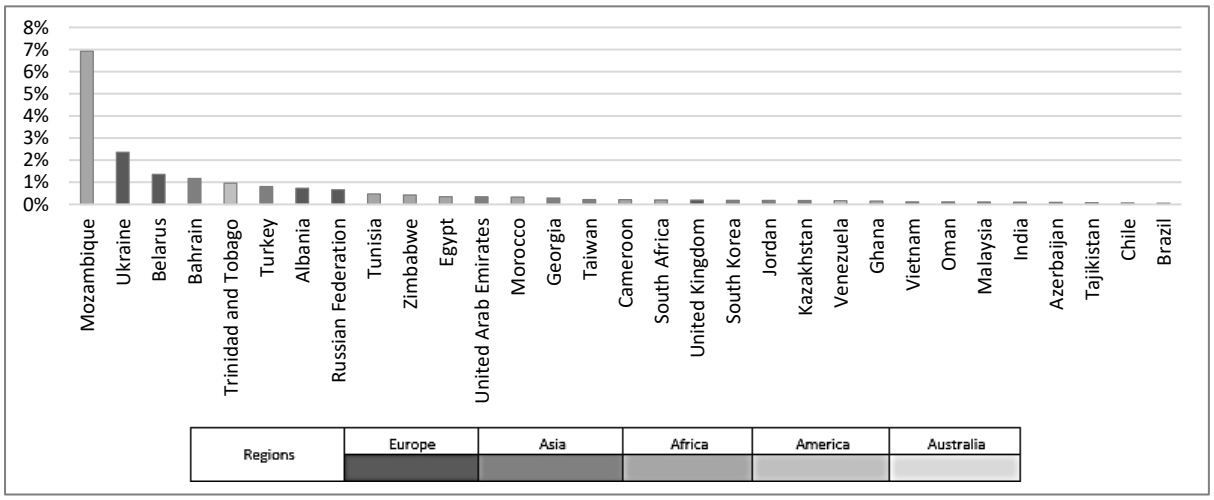

Figure 5. CBAM-affected product exports to the EU (% of GDP).

As shown in Figure 6, Zimbabwe has the highest aggregate Relative CBAM Exposure Index, with a score of 0,0873. It is followed by Ukraine, with a score of 0,525, and Georgia, with a score of 0,0464. This indicates that the additional costs of CBAM implementation for Zimbabwe will be USD 8,73 per ton of CO_2 emissions and USD 4,64 per ton for Georgia. Furthermore, Jordan, Colombia and Albania have the lowest aggregate Relative CBAM Exposure Index (i.e., negative index values less than 0,01). For the vast majority of the observed countries, additional costs from CBAM implementation are less than USD 1 per ton of CO_2 emissions.

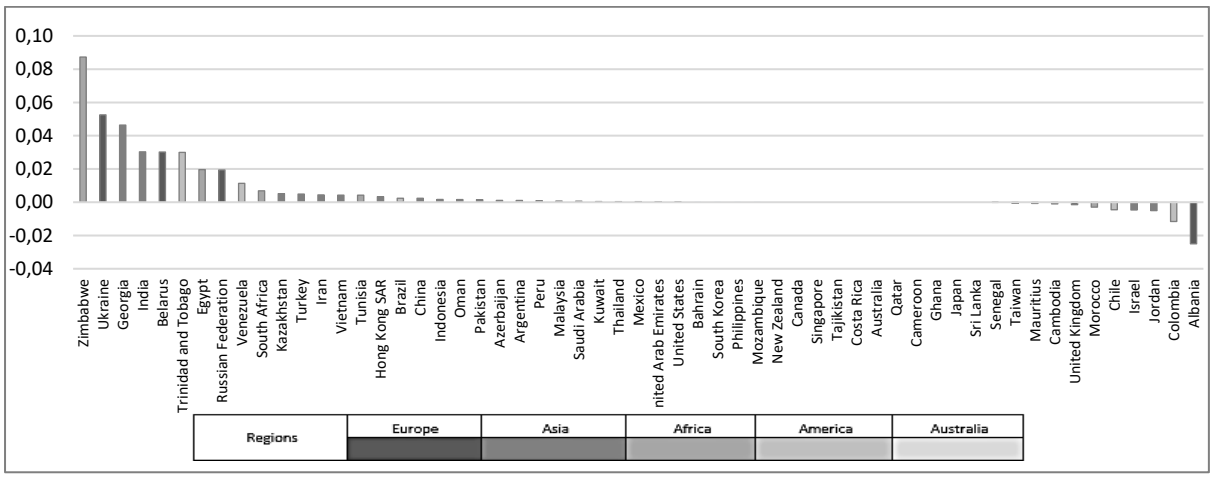

Figure 6. Aggregate Relative CBAM Exposure Index by the selected countries.

CBAM EXPOSURE OF SELECTED ECONOMIES: CROSS-SECTORAL ANALYSIS

The impact of the CBAM could be evident and significant when analyzed across specific sectors, as well as by countries or regions. Sectoral exposures are shown in Table 4, which is based on data on the export of CBAM-affected products. This table identifies the countries most exposed to these products. The analysis includes the following products: aluminum, cement, electricity, fertilizer, iron, and steel. First, the countries are categorized according to their exposure to these CBAM-affected products, followed by an analysis of the export status of these products within individual sectors.

Table 4. Most exposed CBAM-affected products by countries.

Countries	Most exposed CBAM-affected products
Ghana; Kazakhstan; Mozambique; Oman; Tajikistan; United Arab Emirates	Aluminum
Albania; Australia; Bahrain; Belarus; Cameroon; China; Colombia; Israel; Japan; Kuwait; Malaysia; Mauritius; Morocco; Pakistan; Philippines; Qatar; Saudi Arabia; Sri Lanka; Tunisia; Ukraine; United Kingdom; United States	Cement
Russian Federation; Turkey	Electricity
Azerbaijan; Chile; Egypt, Arab Rep.; Georgia; Jordan; Mexico; New Zealand; Trinidad and Tobago	Fertiliser
Argentina; Brazil; Cambodia; Canada; Costa Rica; Hong Kong SAR, China; India; Indonesia; Iran; South Korea; Peru; Senegal; Singapore; South Africa; Taiwan; Thailand; Venezuela; Vietnam; Zimbabwe	Iron and steel

Figure 7 illustrates the export of iron and steel to the EU as a percentage of the total export of these products to the world. Zimbabwe leads with 91,7 % of its total iron and steel exports. Following Zimbabwe are three European countries: Switzerland (77,1 %), Norway (73,3 %), and United Kingdom (66,4 %). Venezuela is the leading exporter of iron and steel from the Americas, with 50,1 % of its exports going to the EU, while Turkey is the leading exporter from Asia, with 43,2 %. The lowest export shares of iron and steel to the EU are recorded by Qatar and Colombia, at 0,6 % and 0,3 %, respectively.

Figure 8 represents the Relative CBAM Exposure Index for iron and steel, excluding countries with an index of zero. Only 16 countries have an exposure index greater than zero, though these countries' scores are generally low. Zimbabwe leads with an exposure index of 0,09, followed by Ukraine with an index of 0,05, and India with an index of 0,04. Only nine countries face an additional cost of CBAM implementation for iron and steel exceeding USD 1 per ton of CO_2 emissions, with Zimbabwe incurring the highest additional cost of USD 9,20 per ton of CO_2 emissions.

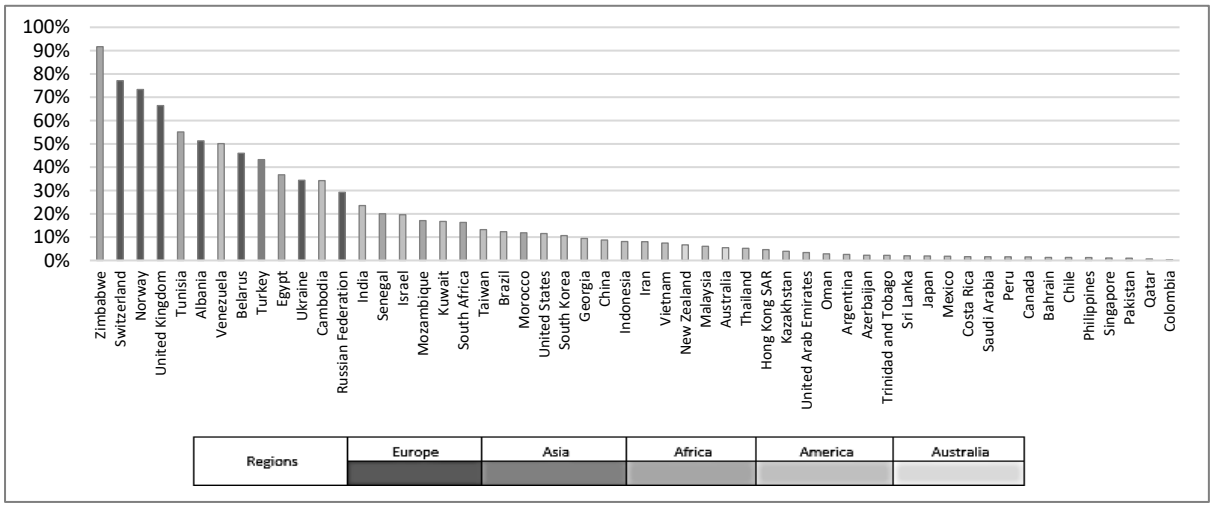

Figure 7. Exports of iron and steel to the EU (% of total iron and steel exports to the world).

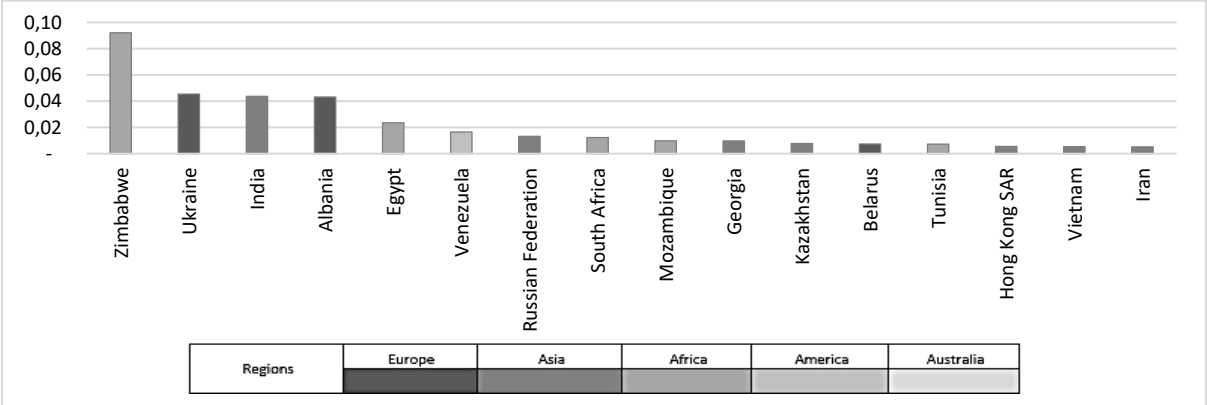

Figure 8. Relative CBAM Exposure Index for iron and steel.

As shown in Figure 9, the European region leads in fertilizer export to the EU, with Belarus exporting 75,3 % and the United Kingdom 67,6 % of their total fertilizer exports to the world. Europe is followed by the Asia region, where Georgia exports 59,5 % of its fertilizer exports to the world. Azerbaijan closely follows with 58,65 %, and Israel with 43 %. In the African region, Tunisia leads with 42,5 %, while in the Americas, Chile exports 29,6 % of its total fertilizer exports. Only 16 countries have more than 10 % of their fertilizer exports to the world.

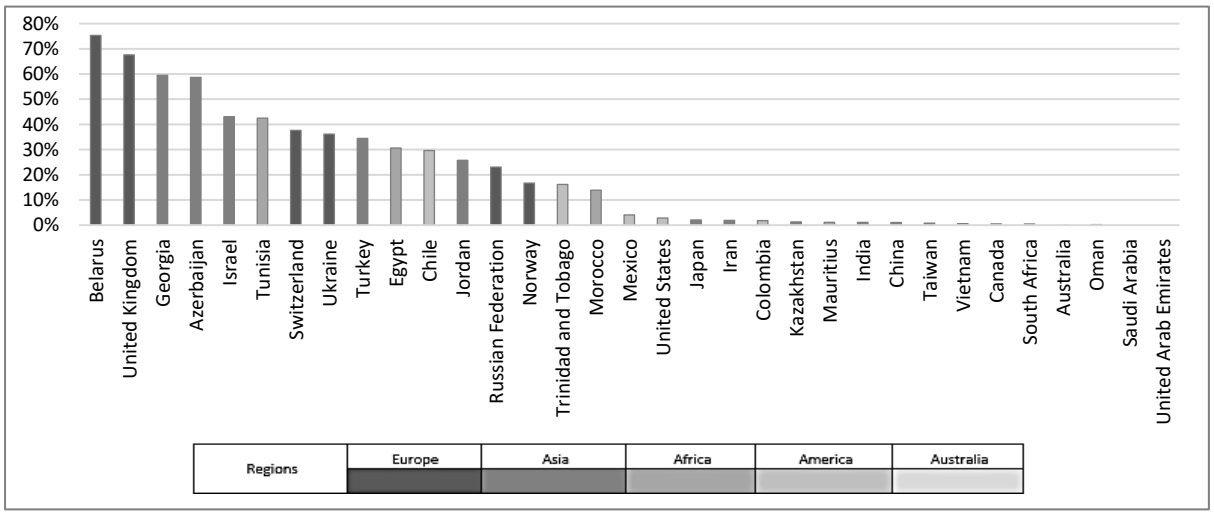

Figure 9. Exports of fertilizer to EU (% of total fertilizer exports to the world).

When looking at the Relative CBAM Exposure Index for fertilizer, as can be seen from Figure 10, Ukraine leads with the highest index of 0,0837. It is followed by Georgia from the Asian region with an index of 0,0814. From the American region, Trinidad and Tobago has the highest exposure index of 0,0436, while in Africa, Egypt has an index of 0,0268. This indicates that Ukraine faces the highest additional cost for exporting fertilizers under the CBAM, amounting to USD 8,37 per ton of CO_2 emissions. Figure 10 includes only countries with a positive exposure index, while ten countries have a negative CBAM relative exposure value for fertilizers.

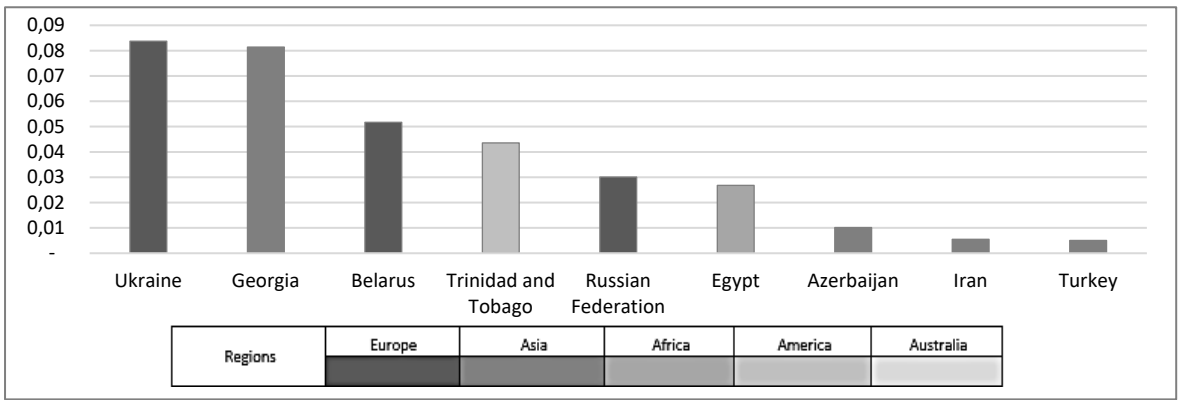

Figure 10. Relative CBAM Exposure Index for fertilizer.

The European region once again leads in terms of relative share in cement exports to the EU, with Ukraine exporting 90,6 % and the United Kingdom 72,1 % of their total cement exports. The Americas follow, led by Colombia with 67,3 %, and Africa by Morocco with 42,9 %. Notably, among 19 countries analyzed, 10 have a cement export share greater than 10 % of their total cement exports, Figure 11.

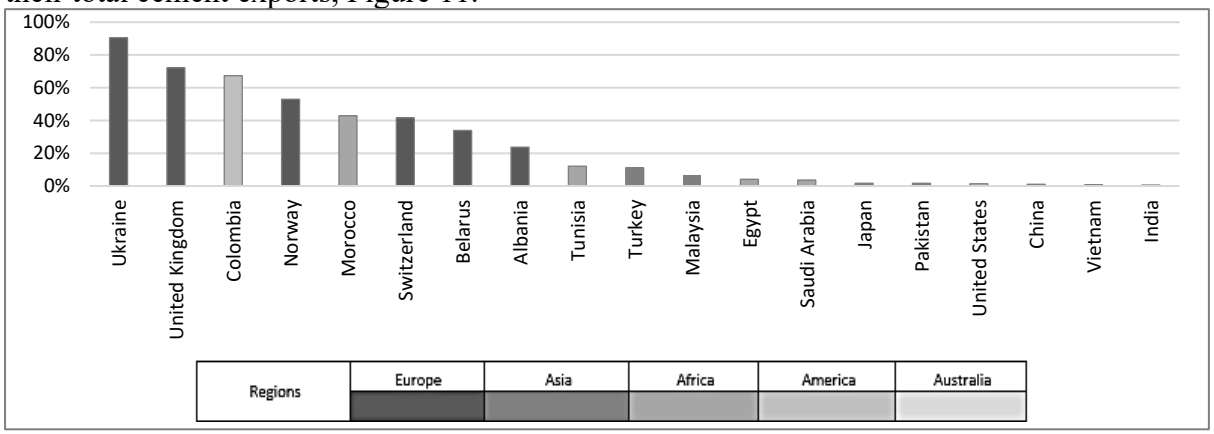

Figure 11. Exports of cement to EU (% of total cement exports).

Furthermore, as Figure 12 reveals, Belarus and Ukraine have the highest Relative CBAM Exposure Index for cement in the European region, with scores of 0,3078 and 0,2397, respectively. They are followed by Malaysia, the Asian region, with an index of 0,0256, and two countries from the African region, Saudi Arabia and Tunisia, with indices of 0,0144 and 0,0078, respectively. Belarus faces the highest additional cost under CBAM for cement, amounting to USD 30,78 per ton of CO_2 emissions.

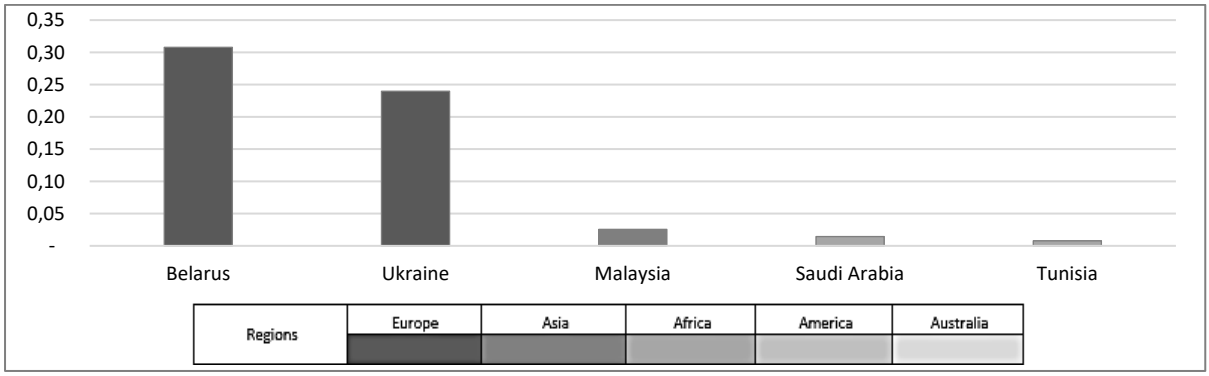

Figure 12. Relative CBAM Exposure Index for cement.

In the aluminum sector, as shown in Figure 13, Mozambique leads with the highest share of exports to the EU as far as the African region is concerned, at 96,6 %, followed by Ghana and Cameron, with shares of 94,8 % and 94,2 %, respectively. From the European region, Norway has a significant share of 93,7 %, while from the American region Venezuela has a share of 41,3 %. Among the 45 countries analyzed in this sector, 22 have a share of aluminum exports to the EU (% of total aluminum exports to the world) that is less than 10 %.

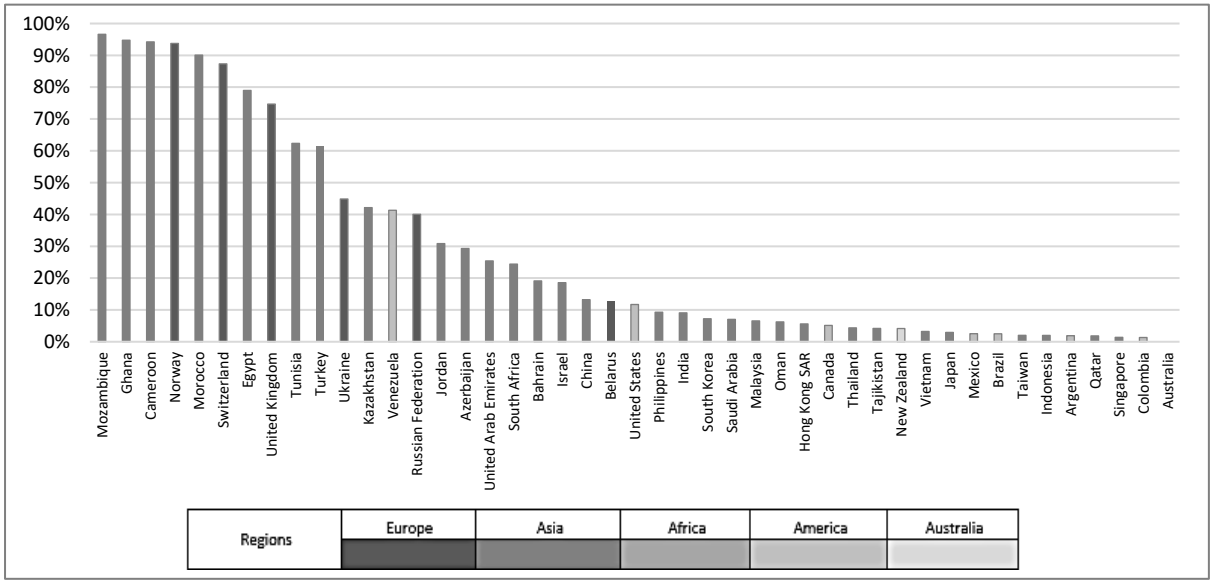

Figure 13. Exports of aluminum to EU (% of total aluminum exports to the world).

Mozambique also leads in the Relative CBAM Aluminum Exposure Index, with a score of 0,5922, Figure 14. It is followed by Kazakhstan and Egypt, with indices of 0,0404 and 0,0143, respectively. From the Americas, Venezuela has the highest exposure index at 0,0132, while considering the European region Ukraine has the highest index of 0,0121. The lowest indices are recorded by the United Kingdom and Ghana, with values of –0,0036 and –0,0046, respectively. Mozambique faces the highest additional cost under the CBAM for aluminum, amounting to USD 59,22 per ton of CO_2 emissions.

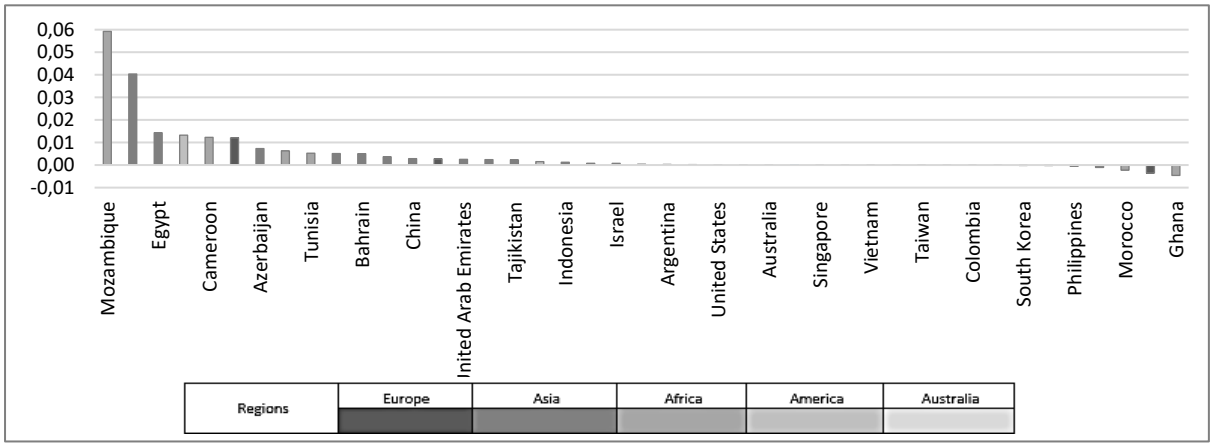

Figure 14. Relative CBAM Exposure Index for aluminum.

The export of electricity to the EU as a percentage of the total world export of electricity is illustrated in Figure 15. Analysis is limited to eight countries, predominantly from Europe and part of Asia. Notably, five of these countries – four from Europe: Belarus, Norway, the United Kingdom, and Ukraine, and one from Asia: Turkey – export 100 % of their electricity to the EU. All these countries have export shares exceeding 73 % of total global electricity exports.

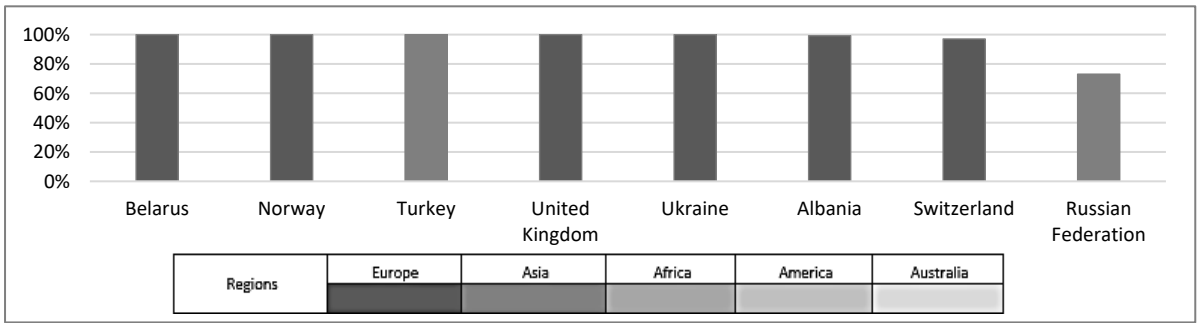

Figure 15. Exports of electricity to EU (percentage of total electricity exports to the world).

In terms of the Relative CBAM Exposure Index for electricity (see Figure 16), the European region leads with the Russian Federation and Turkey from the Asian region recording indices of 0,2257 and 0,2099, respectively. The remaining countries are from the European region, with only Albania showing a negative exposure index of –0,1454. The Russian Federation faces the highest additional cost under the CBAM for electricity, amounting USD 22,57 per ton of CO_2 emissions.

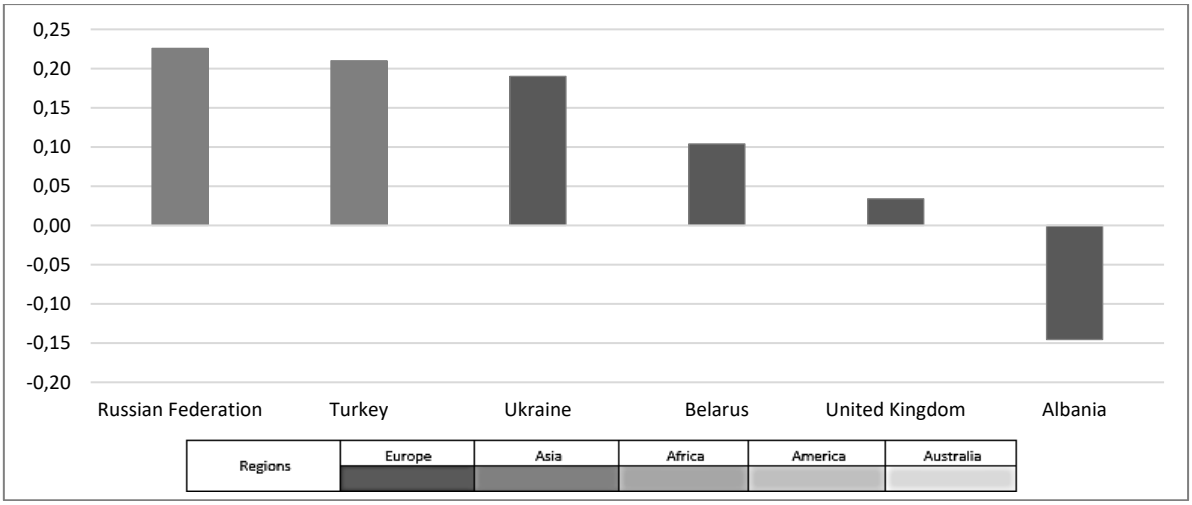

Figure 16. Relative CBAM Exposure Index for electricity.

CONCLUDING REMARKS AND RECOMMENDATIONS

The CBAM can be primarily understood as a measure designed to protect the competitiveness of EU producers in response to strict climate goals and an increase in the carbon price. This measure may favor countries that can decarbonize their production more rapidly and adhere to climate commitments, potentionally leading to trade implications that disproportionately benefit EU countries. The article analyzes the impact of of the CBAM's introduction on the EU's trade partners, with a particular focus on its consequences for a group of selected countries.

The findings indicate that the impact of the CBAM varies depending on the strength of a region's trade relations with Europe. Countries with stronger trade ties, particularly in goods with high CO_2 content, may face greater exposure. Also, some countries have a significant share of sectors that are carbon-intensive, which could result in substantial exposure to the CBAM. For example, Ukraine's fertilizer and cement industries are significantly affected, contributing to the country's overall exposure. Similarly, Zimbabwe leads in CBAM exposure scores, particularly in the iron and steel sector. The entire electricity exports of Belarus, Norway, Turkey, the United Kingdom, and Ukraine are directed to the EU, resulting in high CBAM exposure indices for these countries in the electricity sector. Mozambique stands out as the most exposed aluminum exporter, with 96.6% of its total world export destined for the EU. However, the CO_2 emission intensity of individual countries and sectors is generally lower than the EU average (for example, iron and steel exports from the United Kingdom, fertilizer exports from Israel, cement exports from Colombia, aluminum exports from Ghana, and electricity exports from Albania). The lowest exposure is observed in the Americas and Australia, as these regions are geographically distant from the EU and maintain relatively limited trade relations with the EU.

Additionally, the industrial structure of certain countries is skewed towards higher CO_2 emissions, increasing the likelihood that these countries will be subject to the CBAM in the future. Monitoring and trading of CO_2 emissions remain significant challenges due to the limited capacity for such monitoring and analysis. Possible difficulties in adapting to the CBAM may stem from the absence of mechanisms to reduce carbon emissions or inadequate capacity to measure and report emissions.

These points lead to the conclusion that the primary goal of introducing CBAM is not to reduce environmental or climate impact, but rather to enhance competitiveness and ensure more equitable distribution of income. It is expected that the CBAM will increase production costs both within domestic economies and in the EU market. Moreover, the CBAM has the potential to alter the competitiveness of exporting firms in the EU market. Developed countries generally fare better than developing ones, as their production practices are typically less carbon-intensive. The EU might consider allocating part of the revenue generated from the CBAM to accelerate the spread and adoption of cleaner production technologies in CBAM-targeted sectors within developing economies.

Future research should focus on monitoring the indices discussed in this article over time to observe how they evolve. This will help determine whether countries adopt the proposed mechanisms or develop new strategies to address CO_2 emissions. For decision makers, it is recommended to consider introducing or expanding broad-based domestic carbon pricing programs. While these programs could increase business costs, the revenues generated could suport the functioning of domestic governments and assist exporters in reducing carbon emissions. Furthermore, establishing a fixed carbon price could facilitate investment in green activities and low-carbon technologies, thereby encouraging new investment in the country, etc.

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AAHAR YOJANA: A PERSPECTIVE OF SUBSIDISED MEAL PROGRAMME AMID THE PANDEMIC

Pallavi Kanungo[1,*] and Apparao Thamminaina[2]

[1]National Institute of Technology Rourkela, Humanities and Social Sciences Department
Odisha, India

[2]University of Hyderabad, Department of Anthropology
Telangana, India

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ABSTRACT

The Covid-19 pandemic left millions to suffer its impact in the forms of unemployment, displacement, acute food shortage, and more. It kept migrants and urban poor to remain more vulnerable to food. This study examined the impact of coronavirus on the food security of the urban poor through the lens of Aahar Yojana, one of the government-led subsidised meal programs in Odisha, India. It combined the interview data obtained from the Aahar centres with structured observations and evaluated interlinked elements of the institutional services and pandemic: Hunger satisfaction level, Food hygiene, Sanitation, Quality, and Quantity. Results emphasised integrating such initiatives with robust governmental interventions to shift focus from cash transfers and subsidies. The originality of this paper is that it revealed that the scope of formerly established meal programs could mitigate food insecurity as reflected from the practical benefits during the pandemic.

KEY WORDS

Aahar, meal, subsidised, India, pandemic

CLASSIFICATION

JEL: I38, L66, Q18

*Corresponding author, η: pallavi.kanungo.pk3@gmail.com; 8596884241;
Humanities and Social Sciences Department, National Institute of Technology Rourkela,
769008 Odisha, India

INTRODUCTION

Food insecurity is the situation when 'people lack access to adequate hygienic or nutritious food' [1]. The cause of insecurity varies with food scarcity, pricing, and unequal distribution among family members [2]. To address this significant concern, United Nations adopted eradicating poverty and hunger as one of the Millennium Development Goals (MDGs) goals in 2000. Similarly, the Sustainable Development Goals (SDGs, 2030) also mentioned it with a different spirit. Food insecurity remained a significant challenge with the onset of COVID-19 (Novel Coronavirus Disease). The World Health Organization (WHO) announced it as a pandemic in March 2020. The surge of new strains of positive cases in 2021 became a constant cause of distress [3]. The regimes of every nation initiated similar actions like imposing restrictions on mobility, social distancing, shutdown, and lockdown to curtail its spread. In India, the state governments also initiated independent strategies such as containment zones, control of gatherings in public places, and executing door-to-door assessments to monitor the spread of disease.

Within such regulations, the inflow of migrants, environmental circumstances (drought and storms), and a significant rise in COVID-19 cases left millions of individuals unprepared to suffer economic, social, and food losses and interruptions to essential services. It meant that impoverished people would go hungry, face socioeconomic disparities, and cope with poorer quantity and quality of food intake, which would have a long-term impact. Meanwhile, securing food and getting it to those in need became critical in urban areas. The state governments in India took proactive measures by distributing food and compensating with monetary support to meet nutritional needs. On the other, the potential of existing food distribution programs was untapped during the pandemic. For example, Aahar Kendra, a subsidised meal program launched in 2015, is one such initiative in Odisha. It must adopt context-specific strategies to become an apparatus to mitigate food insecurity amid the pandemic. However, this study revealed a changeable impact of the program that provides insights for future policy interventions.

FOOD SCHEMES AND PROGRAMMES IN INDIA PRIOR TO THE PANDEMIC

The food policy in India geared up after Independence to mitigate hunger and poverty. The long-term strategy embraced plans encompassing food production, improving marketing infrastructure, and institutional mechanisms. The short-term strategy emphasised subsidised food distribution. The country evolved a Public Distribution System (PDS) with a motive to distribute food grains to the Below Poverty Line households. In 1992, the PDS again re-established as the Revamped Public Distribution System with the necessary adjustments. In 1997, it developed into Targeted Public Distribution System (TPDS), under which the government supplied rice, sugar, oil, and other products through fair price shops. Besides, the government initiated several programs and schemes such as *Rashtriya Krishi Vikas Yojana* (RKVY), Emergency Feeding Programs (EFP), *Antodyay Anna Yojana* (AAY), Integrated Schemes of Oilseeds, Pulses, Oil palm, and Maize (ISOPOM), scheme of village grain bank, Integrated Child Development Services (ICDS), National Horticulture Mission (NHM), Mid-day Meal (MDM), and Annapurna scheme to address the challenges of food. Lastly, the National Food Security Act came into force in 2013 with a model shift from welfare to the rights-based approach.

Although India tackled hunger and food insecurity malady [4], the cost, storage, and transportation remained a barrier to viability. Food as an 'essential service' got adversely affected due to Covid-19. Earlier, identifying the deserved beneficiaries of food security was difficult [5], but during the pandemic, it became challenging to relieve people from food insecurity. However, Indian states had a backup of independent subsidised meal programs under different names during the pre-pandemic phase to cater to the urban poor. To name a

few, *Amma* Canteen in Tamil Nadu, *Aahar Kendra* in Odisha, *Atal Jan Aahar Kendra*, *Aam Aadmi* Canteen and *Atal Rasoi Deen Dayal Aahar Kendra* in Delhi, *Annapurna Rasoi Yojana* in Rajasthan, *Mukhyamantri Dal-Bhat Yojana* in Jharkhand, *Indira* Canteen in Karnataka, and *Anna NTR* canteens in Andhra Pradesh. These initiatives are concerned with providing quality food to needy people, migrants, and the urban poor. Some canteens adopted specific hygienic maintenance protocols, for example, prohibiting footwear inside the dining hall. Amma canteens had offered hot water mixed with turmeric, pepper, and ginger during the pandemic. These canteens functioned on a self-serving basis and it is more hygienic than the street food and cafeterias, where cleanliness, access to sanitation, clean water, and waste management received sufficient attention [6-9]. The advantages of such initiatives defend from the fear of food pressure [10] and promote security. Hence, the realisation of this aspect became visible when the pandemic struck the entire world.

BACKGROUND OF *AAHAR KENDRA*

The Odisha Government launched Aahar Kendra (food distribution outlets) for the urban poor in 2015 in Cuttack, Rourkela, Bhubaneswar, Sambalpur, and Berhampur. The meal is available at the subsidised rate of five rupees while the actual cost is twenty rupees. The remaining expenditure is met from local donations and funds available under Corporate Social Responsibility. The meal contains 'Bhāta', i.e., boiled rice, and 'Dālmā', i.e., mixed pulses vegetable curry. In addition, they served pickles and dry snacks on selective days. Its distinct features are quality food, quantity, price, time, hygiene, cleanliness, drinking water facility, and inclusive infrastructure. It is open to all people. However, the primary beneficiaries are wage labourers, construction workers, street children, slum inhabitants, beggars, destitute, rag pickers, scavengers, drivers, patients, attendants, and students. The strategy for setting up these outlets is target-based and area-based. The government opened them near the marketplace, railway station, court, bus depot, and hospitals to ensure access to the needy. The Housing and Urban Development Department is the nodal organisation for implementation. It has multiple partners. They are Odisha Mining Corporation in Bhubaneswar and Cuttack, Odisha Power Generation Corporation (OPGC) in Rourkela, and Industrial Infrastructure Development Corporation in Sambalpur, and Tata Steel Limited in Berhampur [11, 12].

METHODS AND DATA COLLECTION

SELECTION OF RESEARCH AREA

There is an extensive influence of the ongoing pandemic on health, food (supply and prices), education, livelihood, and overall daily life [13, 14]. It can generate a twofold food insecure population due to income loss and anomalies in food schemes and policies [15]. Almost 746 million people experience food insecurity at a severe level. The Asian regions contributed 421,6 million, and 341,8 million belonged to Southern Asia. Following Africa, the South Asian countries have the highest prevalence of severe food insecurity, i.e., 17.8% and nearly 57% of its population fail to afford a healthy diet; thus, producing additional pressure during the pandemic. In developing countries, it is visible amongst low-income households because of two choices, first, striving to earn some money to eat, and second, accepting the risks of stepping out and becoming infected [16, 17]. Among 113 countries, India obtained the 71st rank (56,2 scores) in the Global Food Security Index. Moreover, India's population still suffers from the burden of hunger due to a lack of affordability. India ranked 101st out of the 116 countries, scoring 27,5 that indicated a severe hunger level [18]. The country with TPDS as the most prominent food protection program stood fragile in safeguarding these deprived populations [19]. Hence, access to food for the poor and downtrodden remained critical during the pandemic in various Indian states.

The 'low-income states,' namely Bihar, Odisha, Madhya Pradesh, Chhattisgarh, Uttar Pradesh, Jharkhand, and Rajasthan, often suffer from food shortages. Despite appreciable progress in mitigating poverty in Odisha, it contained impoverished districts [20], and some of its districts remained 'extremely food insecure.' Sundargarh district of Odisha has 50.75% of its population from indigenous groups, and it is one of those districts with inadequate access to food [21]. For this reason, the authors conducted a preliminary study in Rourkela, Sundargarh district. The district has nine aahar outlets. Six of them are in Rourkela. They are near Rourkela Government hospital, Ispat general hospital, Shelter for Urban Homeless (SUH), Odisha State Road Transportation's bus depot in sector 2, Bisra Bus depot, and Vedvyas temple road, Figure 1. The study is significant in the present context because of the following:

1. There exist lesser-known facts regarding the implications of Aahar Kendra.
2. Reports, newspapers, and government websites have only awareness-based studies reflecting no research scope.
3. No study on such initiatives relates to their role during the pandemic.

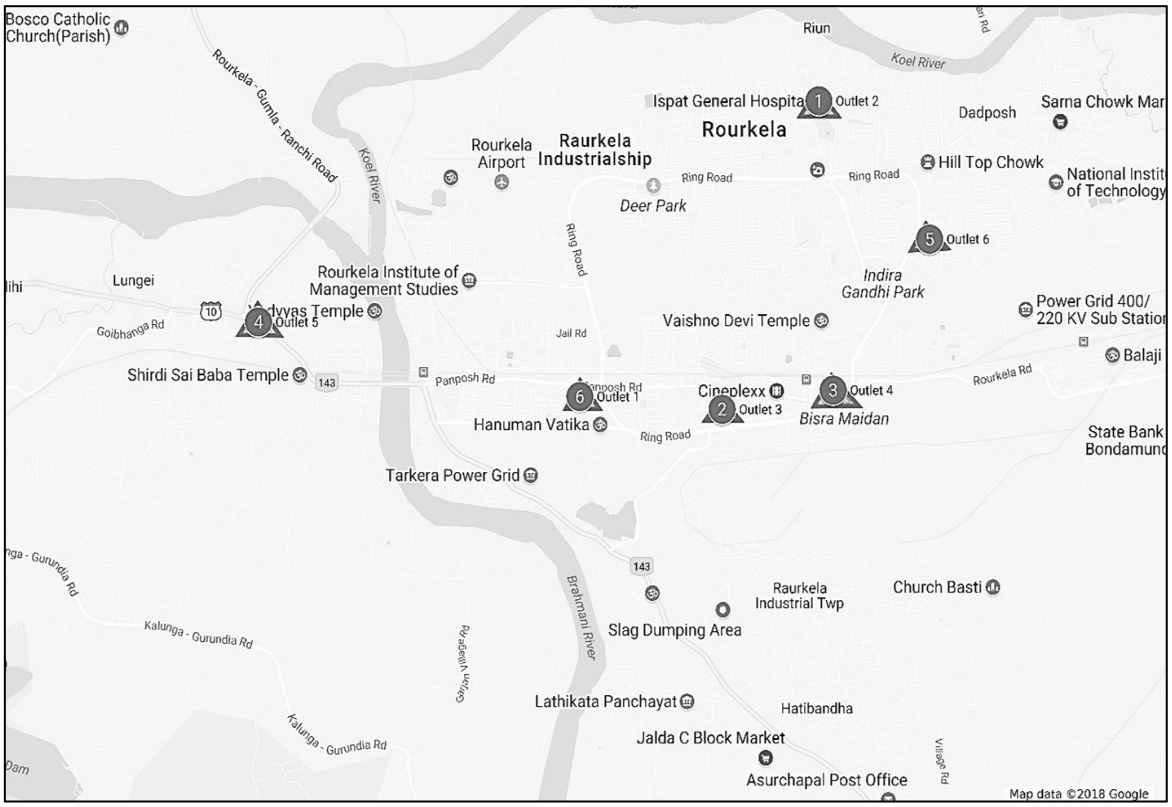

Figure 1. Aahar kendra map showing the six functional outlets in the study area. Source: Author's Representation through GoogleMyMaps; Outlets indicated by numbers

RESEARCH OBJECTIVES

The study has two objectives; they are:

1. To understand the functions of aahar kendra and outline its pros and cons;
2. To examine the impact of the Covid-19 pandemic on food security through Aahar Kendra

This article emphasises the prospects of a subsidised meal program during the outbreak of unwarranted situations such as pandemics.

DATA COLLECTION AND ANALYSIS PROCEDURE

The authors' collected primary data using direct observations and interviews. An aggregate of 110 beneficiaries and 11 associated members of the outlets in Rourkela participated in the

personal interviews. Further, interviews with key stakeholders of the Akshaya Patra Foundation, Rourkela Municipal Corporation (RMC), and District Aahar Society enriched the outcomes with the institutional perspective. The paper highlighted five variables: gender, age, residence, occupation, and frequency of visits. Additionally, the Likert scale analysed five elements, i.e., hunger satisfaction level, hygiene, sanitation, quality, and quantity. The respondents iterated about the sub-elements of five selected elements on a 5-point Likert scale. Lastly, it triangulated the primary data with the secondary data to attain the scope for policy interventions, Table 1.

Table 1. Summary of the present study and data collection procedures.

Sl. no.	Particulars	Key Areas
1.	Primary Objective	Benefits of Aahar Kendra amid Covid-19 pandemic
2.	Area of Analysis	Six outlets of Aahar Kendra in Rourkela (Sundargarh district in Odisha, India)
3.	Total Respondents	110
4.	Inclusion Criteria based on Objectives	Beneficiaries present at the Aahar Kendra site
5.	Data collection method and Duration of Observation and Personal Interview	**A.** Phase 1 (interview method, Two months-questions about situations during pre-pandemic) **B*** Phase 2 (questions about situations during the pandemic and structured observations for Three weeks). **C.** Phase 3 (Post-pandemic Discussion)
6.	Statistical Methods and Software used	Likert Scale, SPSS 20
7.	Description of Likert Analysis	E.g. Satisfied with a given quantity is the final variable. It had three elements measured under the Likert scale (i.e. Quantity of Rice, Quantity of Dālmā, Quantity of pickle/dry mixture) and the Scale value (4 – Excellent; 3 – Good; 2 – Neutral; 1 – Fair and 0 – Bad).
8.	Results	Quantitative and Qualitative analysis

*Structured observations assisted in the ongoing pandemic phase as the interview affected by lockdown, shutdown, night curfew, and daytime restrictions.

RESULTS AND ANALYSIS

FUNCTIONS OF AAHAR KENDRA

The Odisha State Aahar Society (OSAS) is the executive agency and governing body at the state level under which the outlets' function. It monitored the activities of the District Aahar Society (DAS). The DAS regulated the outlets in Rourkela by mobilising funds from the contributing agencies to meet the subsidy expenditure. The RMC handled the infrastructural management system (record maintenance, supervising employees, redressing grievances, and maintaining infrastructure, fans, coolers, dishwashers, surveillance cameras, and television). The primary sponsor is OPGC, while Touchstone Foundation implemented the program. The Akshaya Patra Foundation (an associate unit of Touchstone Foundation) prepared and distributed food to outlets in the city. Its prime function is maintaining an equilibrium between food, hygiene, and housekeeping. The foundation has employed a supervisor at each centre

(five outlets have male supervisors, and one has a female supervisor). The serving staff worked rotationally in each centre. Primarily, female members worked as housekeeping staff, and they were limited to two in each centre. The implementing agencies continuously trained the staff in association and support from the Housing and Urban Development Department, Figure 2.

PROS AND CONS OF AAHAR KENDRA (PRE-PANDEMIC)

1. **Pros –** These establishments prepare and serve meals to beneficiaries on time. They serve approximately 6000 beneficiaries every day in Rourkela. The amount of food prepared varies with the growing or falling demand. The quantity of each food item (rice and curry) has a fixed measuring unit vessel per serving. One container of hot cooked meals caters to up to 47 beneficiaries, with an approximate serving of 200 gm. of rice and 60 gm. of curry per beneficiary. The quality analyst examines the pesticide and insecticide deposits in vegetables and submits the quality assurance report relying on which the organisation purchases vegetables to prevent food poisoning. Akshaya Patra Foundation provided training-cum exposure visits to its centralised kitchen for staff on cooking, hygiene, and rules and regulations. To ensure hygiene, aahar kendra and Akshaya Patra Foundation employees wear hair caps and face masks when cooking and serving. The centres ensure cleanliness for every visitor with continuous sweeping and mopping. Beneficiaries wash their dishes after meals, making them accountable for their cleanliness. These outlets also have the facility to sterilise the utensils. The foundation converts the food waste into biogas.
2. **Cons –** The viability of this program is heavily reliant on financial assistance, making it difficult for the OSAS and DAS to raise funds when inconsistencies in contribution develop. Housekeeping personnel hired on a contract basis often complained about irregularity in payment with lesser salaries. In a few cases, staffs do not attend duties on time. Hence, they compromise on hygiene during peak hours. Inadequate supervision is a barrier to maintaining the goodwill of this initiative. Food wastage, dependency on cash and kind transfers, and failure to efficiently use human resources limited its advantages. Sadly, grievances redressal and appraisal mechanisms are inactive. Employees and beneficiaries are hesitant to register grievances because they believe it would result in the program's termination. It produces a negligent attitude that will be counterproductive. The outlets do not have additional safety measures (e.g., security guard, fire extinguisher) for contingencies. Lastly, the outcomes revealed that the people's ability to afford food and maintain these centres had less pressure on the state during the pre-pandemic phase. Nevertheless, it is necessary to examine these factors to draw any firm inferences on the post-pandemic phase, Figure 2.

Despite differences among families in managing food uncertainties, the correlation analysis showed a general sequencing of the events. Results indicated that age did not have any effect on the selected variables. Gender is essential in determining cleanliness and safety; this is because female peers are more concerned with cleanliness compared to men. In Indian society, women in the households remain responsible for cleanliness. Hence, the negative correlation is due to the dissatisfaction of female visitors with the hygiene of food, especially the cleanliness of utensils. It implied a distinct perception of gender regarding their food hygiene. This result is also consistent with the findings of authors [22], who discussed the direct relationship between women and their limited dining out habits. Indeed, variations in food intake location had a connection with gender in terms of assessing the risk of having COVID-19 [23].

At the pre-pandemic time, the occupational situation of the categories of beneficiaries had a varied effect on their access to food. However, the outlet served the urban poor without constricting their access to food and compromising hygiene during the pandemic. The type of residence positively correlated with the frequency of visits as more residents from slums had their meals at these outlets more frequently. Apart from it, the frequency of visits positively

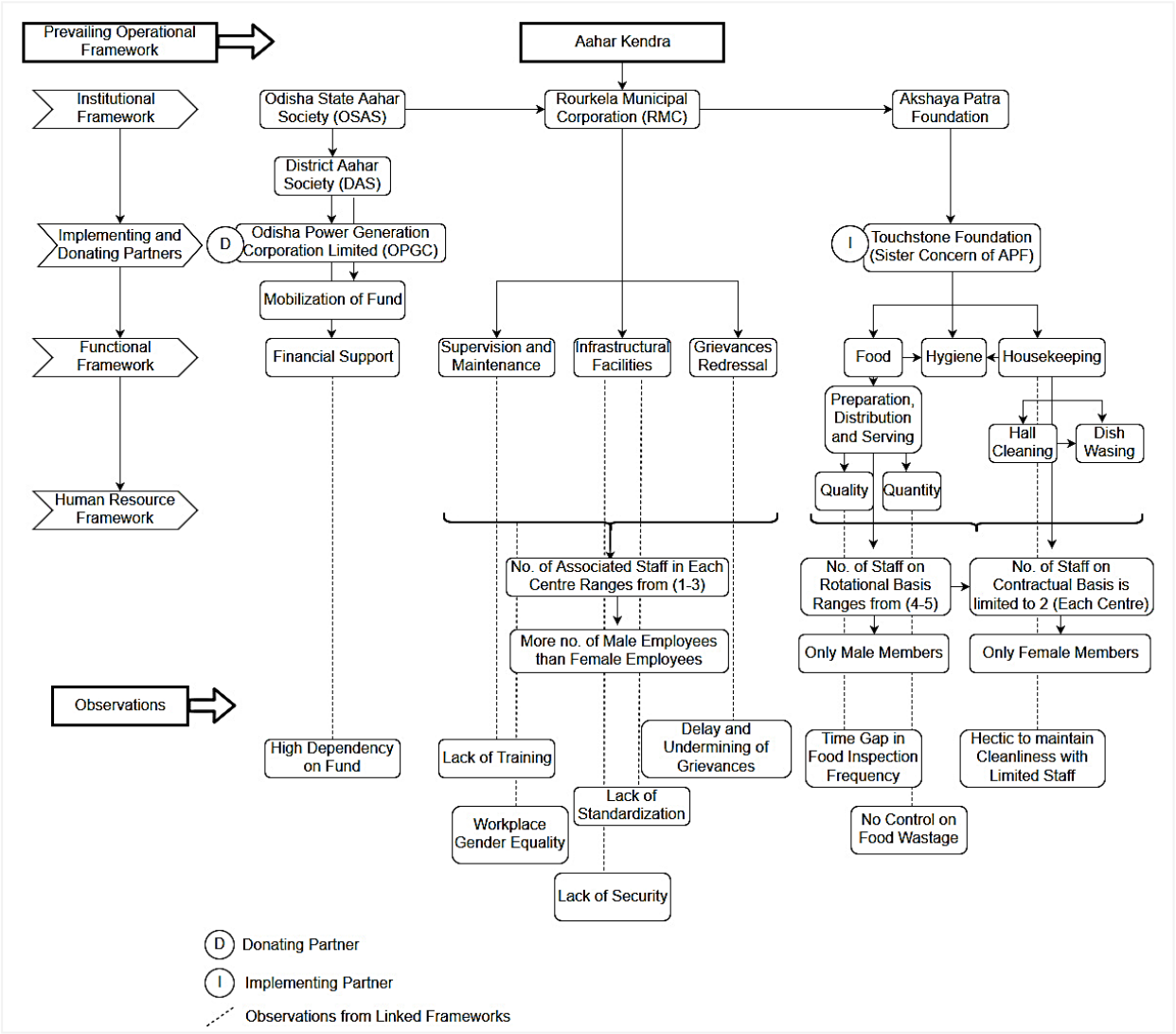

Figure 2. Outline of observations and integrated functions of aahar kendra reflecting the pros and cons.

correlated with five elements: hunger satisfaction, food hygiene, the quantity of food, quality of food, and sanitation. This evidence is in line with earlier finding [9], where the author mentioned in the case study that low-income groups had the opportunity to afford hygienically cooked and nutritious meals in similar canteens without depending on leftover food. Hence, the cumulative satisfaction over these elements aided the lower-income groups to have their meal frequently at these outlets and save time and money from travelling back home to work only for food. Similarly, the respondents believed that the hunger satisfaction level positively correlated to food hygiene and quality, Table 2.

IMPACT OF COVID-19 ON AAHAR YOJANA AND ITS CHANGING ROLE (DURING & POST-PANDEMIC)

This section is about positioning the poor, migrants, and returnees to report their food accessibility alternatives. We know that pandemic made us work from home, and it became a 'new normal' for millennial. On the other, most of the population had no option for this. The declaration of the shutdown in the country made the working-class population jobless. The unforeseen exigency left a part of the population with no means to afford food for their family. This chaos led the regimes to ensure primary care through food, transportation, and shelter in relief camps. The mass exodus influenced the retention of the workforce, overall production, and transportation facilities resulting in an immense loss in food demand and supply chains.

Table 2. Correlation analysis on the responses from phase 1: pre-pandemic scenario.

Variable	Age	Gender	Categories	Residence	Frequency of Visit	Hunger Satisfaction	Food Hygiene	Quantity of Given Food	Quality of Given Food	Overall Sanitation
Age	-	–0,167	–0,025	–0,083	–0,018	0,071	0,066	0,033	0,122	0,111
Gender		-	–0,121	–0,185	0,002	–0,051	**–0,342*** **	0,181	–0,040	0,019
Category			-	–0,092	–0,011	0,035	**0,231***	–0,048	$2{,}963 \cdot 10^{-4}$	–0,137
Residence				-	**0,263****	–0,053	0,023	–0,074	–0,093	–0,033
Frequency of Visit					-	**0,397*****	**0,340*****	**0,335*****	**0,258***	**0,283****
Hunger Satisfaction						-	**0,414*****	0,185	**0,539****	0,243
Food Hygiene							-	0,114	**0,319****	**0,273***
Quantity								-	**0,414*****	**0,230***
Quality									-	**0,276*****
Overall Sanitation										-

*significant at the level $p < 0{,}05$
**significant at the level $p < 0{,}01$
***significant at the level $p < 0{,}001$

Therefore, jobs and livelihoods remained at a higher risk, influencing consumer and supplier behaviour towards food priorities. The skyrocketing prices of essential items and reduced income interrupted the food security of deprived households. The authors provided a comprehensive comparison of various eateries with the initiative to emphasise this point, as expressed in the following paragraphs.

The daily expenses of feeding oneself at the usual time outside the home revolve around five elements: preference for the type of food outlet, price of food, quality, quantity, and hygiene. Amid COVID-19, there was a permanent closure of eateries. Nevertheless, opening eateries for online orders facilitated contactless ordering, hygienic food, or environment, and safe handling practices became the safety net for the customers. The home delivery and pickup services prevented footfall. However, online ordering from eateries was the first choice amongst the well-off and young population. The option left for the working class was 'Dhaba' (roadside hotels), which serve food at a lesser price than the restaurants. However, quality, hygiene, and distance remained a concern. Many small-scale entrepreneurs opened domestic canteens to provide food at a low cost but are congested and prone to risk. It is the same for the street vendor, with no healthy food options, limited quantity, low quality, and unhygienic. The four ways of securing food were not suitable for the low-income groups during Covid-19; thus, it is essential to supply hygienic food at a minimal rate.

The significant observations revealed that hygienic practices prevailed in the outlets. They continued to provide meals to the needy during the pandemic and managed well with the takeaways option. Beneficiaries appreciated this action of the State government. These centres stood as quick-serve, distinct, and oriented toward poor people. The affordable, people-centric, need-based model complied with the nutritional needs and hygiene (wearing masks while cooking and serving food, the distance between seats or as per availability of tokens, hand wash facilities, sterilisation of utensils, and disinfecting of dining halls), became a feasible selection, Figure 3. Envisioning its long-term benefits, the Odisha Government extended the operational timings of the outlets in some areas. Positively, this pandemic brought the benefits of aahar outlets to the forefront. However, its success greatly depended on the state's interest in investing in such subsidised canteens. However, the pandemic has put this initiative to the test, which may quicken its transition to a more sustainable food system in the future.

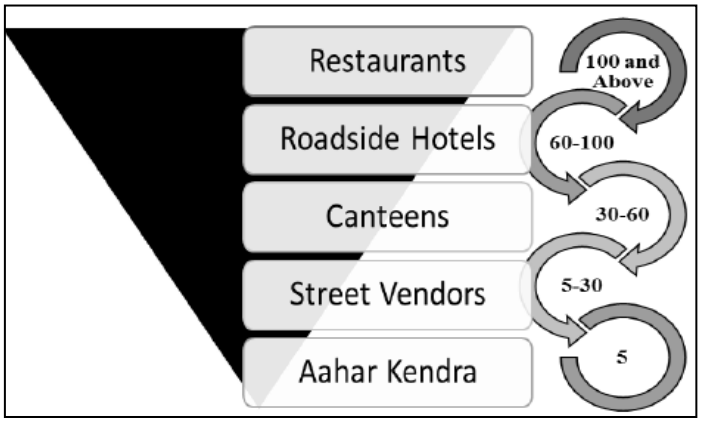

Figure 3. Inverted model on price incurred on daily basis per meal at various food outlets in comparison to the aahar outlet.

CONCLUSION

The food security plan often aims at the rural poor, but this study reflected the needs of the urban poor. The overlapping vulnerabilities during the pandemic deteriorated the conditions of deprived sections in the cities and affected their capability to afford food. The findings revealed that such initiatives would significantly affect other eateries and restaurants in the long term [24].

Few studies suggested converting these 'untargeted' schemes to improve outreach efficiency by identifying only the intended beneficiaries [25]. Similarly, the public envisioned that those who could afford food might opt out of the subsidised meal, but the pandemic proved this wrong as it functioned as intrinsic support for all. The pandemic provided an opportunity to think about reforming the food security system. The subsidised food outlets in collaboration with NGOs could successfully reach the target group in the future. The empirical evidence suggested that the beneficiaries belonged to various sections. This initiative laid new pathways to ensure food security. The most apparent change due to the pandemic is the consciousness of hygiene alongside food security. The Aahar outlets being cleaner and safer could become more efficient by extending their coverage innovatively, e.g., by engaging women's self-help groups in setting up community kitchens. The program can also focus on integrating the rights over food with the job guarantee schemes to build human capacity, increase purchasing power, and ensure food security. This opportunity, to some extent, may tackle the food crisis by maximising the local impact, Figure 4. Though the article limited its data to outlets from a single district, the findings and recommendations will provide governments, stakeholders, and funding organisations with timely information to renew their subsidised meal strategies.

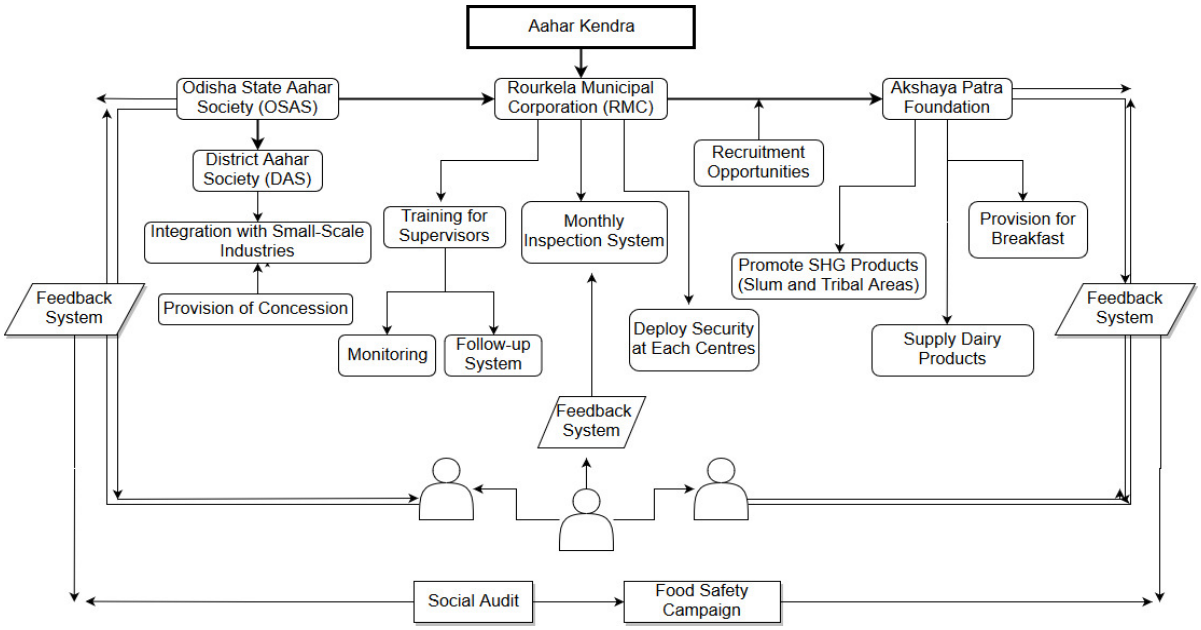

Figure 4. Model for reforming the aahar outlets to make the subsidised meal system effective.

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SERVICE RECOVERY IN TOURISM: A BIBLIOMETRIC-BASED SYSTEMATIC REVIEW AND RESEARCH AGENDA

Emre Tankus[1, *], Ilker Ozturk[2], Dogan Baran Mengus[3] and Alptekin Sokmen[4, 5]

[1]Kastamonu University, Faculty of Tourism, Department of Tourism Management
Kastamonu, Türkiye

[2]Sivas Cumhuriyet University, Cumhuriyet Social Sciences Vocational School, Department of Hotel, Restaurant and Catering Services
Sivas, Türkiye

[3]Tilburg University, Department of Private, Business & Labour Law
Tilburg, The Netherlands

[4]Ankara Hacı Bayram Veli University, Faculty of Economics and Administrative Sciences, Department of Business Administration
Ankara, Türkiye

[5]Kastamonu University, Faculty of Tourism, Department of Tourism Management, Administration
Ankara, Türkiye

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ABSTRACT

Purpose: This study aims to eliminate the gap in this field by examining the concept of service recovery in the field of tourism with bibliometric technique. **Design/methodology/approach:** This study, data was obtained from the Web of Science database was used in the study. From this perspective, 247 articles in the field of tourism were included in the study and a systematic literature review of the articles was conducted. VOSviewer program was used to make bibliometric mapping of publications produced within the scope of this specific subject and discipline. **Findings:** Five clusters representing the research were identified. Additionally, the study identifies some gaps in the existing literature and provides a framework for future research. Expanding the digital, sustainability and legal dimensions of service recovery, better understanding the mechanisms, and examining recovery strategies as an investment are suggested as promising areas for future research. In this context, the study suggests guiding actions for researchers by identifying future research directions and the advantages it can provide to managers. **Originality/value:** The contribution of this article is to guide stakeholders who want to learn about this topic through the specific clusters created within the scope of co-citation relationships and the labels that represent them. It will also contribute to the emergence of new ideas that can guide researchers on service recovery.

KEY WORDS

service recovery, bibliometric analysis, tourism

CLASSIFICATION

JEL: Z31

*Corresponding author, η: etankus@sinop.edu.tr;+90(533)4832396;
Sinop Üniversitesi Gerze Meslek Yüksekokulu, 57600 Gerze/Sinop, Türkiye

INTRODUCTION

Businesses operating in the service sector try to provide the best service to their customers. However, in businesses that set out with the concept of zero error, service disruptions occur from time to time. Even though businesses avoid making mistakes, the characteristics and labor-intensive nature of the service create some disruptions. As a matter of fact, disruptions may negatively affect customer satisfaction and business image. These negative disruptions cost customers money and time, hence results in economic/financial losses for the customer [1]. Service failures can have serious financial consequences on customers, including missed business opportunities, alternative transportation and accommodation costs, ticket refunds, lost vacation days or increased travel expenses, all of which can negatively impact an individual's financial situation [2]. For example, on a trip where there was a service failure, the tourism office asked the tour agency to pay recovery of $60 to each tourist ($18,000 in total). Another example shows that the recovery awarded can reach very large amounts. The court decided to pay approximately 30 million US dollars to the airline company that caused the service failure. The recovery paid may not be considered a significant amount for large enterprises; however, negative impressions and roumors has the potential to cause more harm than the recovery paid [3]. These customers transfer their negative experiences to third parties, causing great losses to the industry. These losses reach up to 75 billion dollars in the United States and 37 billion pounds in the United Kingdom [4]. However, when customers receive better service recovery, their negative attitudes change and their opinions about the business become positive [5]. A study shows that when customers have a major complaint, 91% do not buy from you again; however, it was found that if this failure was resolved quickly, 82% would engage in repeat purchasing activity. It has been observed that as the complaint resolution time decreases, the customer dissatisfaction rate also decreases. According to the same research, while the rate of customer dissatisfaction after a complaint is 91%, this rate decreases to 18% if the complaint is resolved quickly [6]. For this reason, service recovery is one of the basic methods used to correct errors that occur in service delivery. In this context, service recovery, when applied with the right methods, can help businesses turn the customer's negative attitude into a positive one [7,8]. In this context, this study emphasizes how critical an issue businesses' service failures are from their perspective and has the potential to contribute to service recovery practices. This study, based on to what extent service recovery has been studied academically in the tourism sector, will guide future studies. It also contributes to the field by taking a broader perspective within the scope of the literature. Studies have been carried out to examine service recovery with an interdisciplinary integrated model and to connect important research themes in this field, but studies in the tourism sector have remained limited. For this reason, in the study, the bibliometric review approach was used specifically for the concept of service recovery and it is aimed to systematically review the articles containing the concept with a bibliometric approach. For this purpose, three research questions were created. According to this:

RQ_1: Which countries, journals, authors, and organizations dominate service recovery research?

RQ_2: What are the prominent thematic clusters in this field, and how do these interact conceptually?

RQ_3: What are the avenues for future research?

This study adds several advances in service recovery for the tourism sector. First, we identify service improvement research by selecting tourism among interdisciplinary publications. We then uncover 5 research clusters to understand the holistic understanding of service recovery. In the final stage, inferences for future research were made as a result of the findings, and the findings, theoretical and practical results of the study were presented.

METHODOLOGY AND FINDINGS

The data required to answer the research questions were obtained from the Web of Science (WoS) database. WoS is a resource known as a bibliometric database and contains citation data. This database is widely preferred in the analysis of academic publications and research [9, 10]. In the study, VOSviewer (version 1.6.19) software developed by Ness Jan van Eck and Ludo Waltman [11] was used to make visualizations on similar topics. VOSviewer is software specifically designed for the creation and visualization of bibliometric maps. To find an answer to the first question of the study, the obtained articles were transferred to the VOSviewer program and their citation and connection strengths were determined by mapping method according to country and place of publication. At this stage bibliographic coupling was used. This technique was chosen because it examines common references or citations in the bibliography lists of different academic publications that cover similar topics and determines the relationship between these works. For the second question of the study, the VOSviewer program was used again. In order to strengthen the relationship network in the formation of the number of clusters during the mapping phase, the minimum number of citations of a cited reference was determined to be at least ten. As a result of the analysis, 5 clusters consist of 166 articles. However, 10 articles in the clusters were removed from the data group as a result of being marked as undefined data. 5 clusters consisting of 156 articles and relevant authors were obtained. The cluster names created at this stage were formed as a result of the research authors' in-depth examination of the articles in the clusters. Researchers created cluster titles by taking into account the topics covered in the relevant articles and the frequencies of the keywords. For the last question of the study, the researchers discussed what new ideas could be put forward on the concept of service recovery.

LITERATURE SELECTION

According to the adopted protocol, literature selection is carried out in three stages: screening phase, curation phase and analysis of the sample [12]. WoS database was preferred in the research and literature was obtained using the topic search category.

Phase I – Scanning Phase

In the query made under the title "service recovery" in the topic search category in the WoS database, it was seen that there was a total of 1659 articles. The search included articles, conference proceedings, review articles, book chapters, proceedings, etc. published in various research fields, including management, geology, social sciences, and environmental studies. The data used in the study was obtained by accessing the relevant network on October 1, 2023.

Phase II – Curating Phase

In the study, several filters were applied to limit the results obtained in the previous step. In order to obtain a reliable result, we focused only on journal articles. The subject area of the research is limited to the fields of hospitality, entertainment, sports and tourism. Considering the number of articles obtained, no year limitation was made. However, 2023 data reflects articles published between January and September. Thus, the search string was determined as "service recovery" (Topic) and Hospitality Leisure Sport Tourism (Web of Science Categories) and Article (Document Types). As a result of the applied filters, 247 articles were obtained. The distribution of these articles by years and number of articles is presented in Figure 1. Accordingly, it can be seen that the number of articles was at the lowest level with two articles in 2005 and at the highest level with 29 articles in 2021. When the status of the concept in the graph is examined, especially in recent years, it is observed that it has reached even digits, but it does not appear to have experienced a continuous increase.

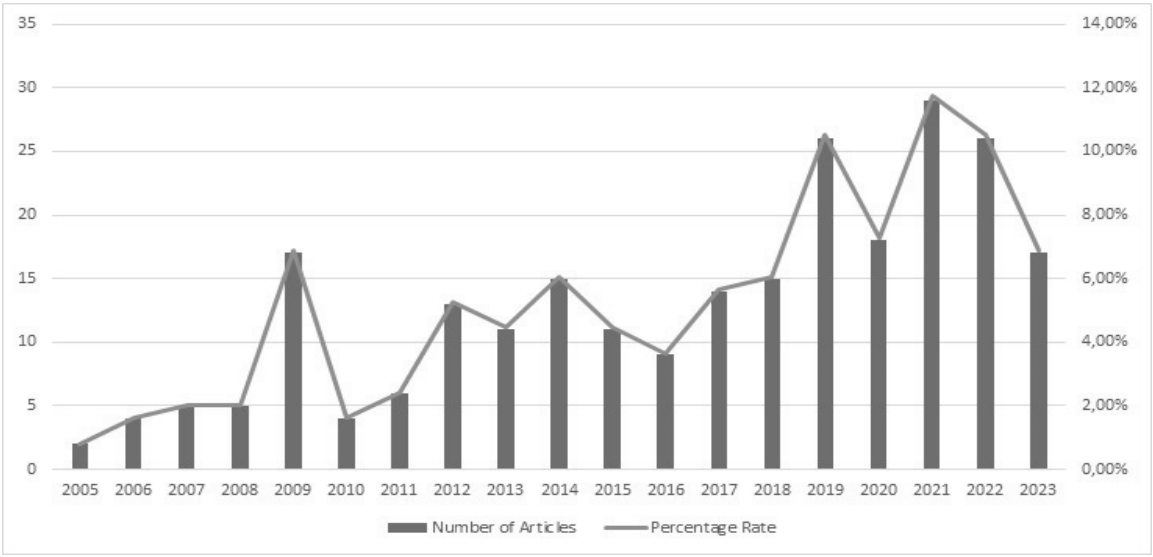

Figure 1. Distribution of service recovery search title by years.

Phase III – Analyzing Phase

When Figure 1 is examined, it is seen that the first article in our sample was published in 2005. Considering the number of publications, it is observed that awareness and interest in the concept increased among researchers, especially between 2019 and 2022. 45 of these publications appear in the h-index. The sample of the study includes 517 authors, 302 affiliations, 48 countries and 43 publication titles. In Table 1, we list the top 10 contributors i.e. authors, organizations, countries, and publication titles service recovery tourism research based on the Total Publication (TP) count.

Table 1. Top 10 authors, organizations, countries, and journals by publication count.

Author	TP	Organization	TP	Country	TP	Puplication Title	TP
Guchait, P.	17	Pennsylvanıa Commonwealth System of Higher Education	24	USA	118	International Journal of Hospitality Management	48
Karatepe, O.M.	17	State University System of Florida	20	China	51	International Journal of Contemporary Hospitality Management	34
Mattila, A.S.	9	Unıversity of Houston	19	Turkey	35	Journal of Hospitality Marketing Management	15
Jang, S.	8	University of Houston System	19	Australia	25	Journal of Hospitality and Tourism Management	13
Pasamehmetoglu, A.	8	Eastern Mediterranean University	17	South Korea	22	Tourism Management	13
Wang, X.Y.	7	Hong Kong Polytechnic University	17	England	17	Cornell Hospitality Quarterly	12
Kim, T.	5	Pennsylvania State University	17	Taiwan	12	Journal of Hospitality Tourism Research	12
Law, R.	5	Unıversity Of Central Florida	16	Malaysia	10	Journal of Quality Assurance in Hospitality Tourism	12
Lee, G.	5	Pennsylvania State University Park	14	Spain	8	Journal of Travel Tourism Marketing	11
Nikbin, D.	5	Purdue University	12	Canada	5	Annals of Tourism Research	9

BIBLIOMETRIC ANALYSIS

Bibliographic coupling

The total link strength (TLS) feature refers to the total strength of a researcher's co-authorship connections with other researchers. It is the sum of the strength of the researcher's connections with other researchers. For example, if a researcher has 10 co-authorship affiliations, each affiliation may have a certain strength. The total connection strength feature shows the sum of the strength of these connections [11]. Table 2 lists the authors, organizations, publication titles, and countries featured in the collected sample. This ranking is made according to TLS.

Table 2. Most prolific authors, organizations and countries by bibliographic link.

Author	TLS	Organization	TLS	Country	TLS
Guchait, P.	26 562	Pennsylvania State University	18 405	USA	58 399
Anna S. Mattila	17 788	Houston University	16 875	China	29 451
Nikbin, D.	14 681	Hong Kong Polytechnic University	16 128	South Korea	20 730
Karatepe O.	13 105	Florida University	13 460	Australia	17 516
Hyun, S.S.	11 509	Purdue University	10 569	Turkey	17 486
Jang S.C.S.	11 304	University Sains Malaysia	9 759	England	14 002
Pasamehmetoglu, A.	11 227	Washington State University	9 378	Malaysia	10 575
Marimuthu, M.	10 137	Sun Yat-Sen University	9 270	Spain	7 295
Ismail, I.	10 137	Eastern Mediterranean University	8 186	Taiwan	7 267
Xingyu, W.	9 795	University South Carolina	7 942	Iran	4 652

Citation analysis

This analysis tracks the number of citations a document has received each year since its publication date, showing how frequently the document is referenced and how often it is referenced by other works. Table 3 highlights the most prolific and influential authors, organizations, and countries based on citation analysis of the top ten. Guchait, P. stood out as the most influential author in our sample, followed by Kim, T.T. and Jang S.C.S. is following. Institutions include University of Houston, University of Houston and Washington State University. In the ranking made according to the country-based TLS rate, they are listed as the United States, China and Turkey. This method ranks the popularity of a work based solely on the citations it receives. It assumes that foundational studies within a field will receive more citations. However, this approach is aimed at old studies and does not take into account the content of the study [12].

Table 3. The most productive authors, organizations and countries according to citation analysis.

Author	TLS	Organization	TLS	Country	TLS
Guchait, P.	401	Houston University	254	USA	712
Kim,T.T.	228	Florida University	147	China	301
Jang S.C.S.	186	Washington State University	145	Turkey	210
Pasamehmetoglu, A.	175	Hong Kong Polytech University	139	South Korea	205
Karatepe O.	174	Purdue University	134	England	153
Xingyu, W.	153	Florida University	133	Australia	144
Anna S. Mattila	141	Penn State University	132	Taiwan	82
Kim, W.G.	140	Özyeğin University	120	Iran	54
Kim, H.	125	Eastern Mediterranean University	114	Spain	53
Lee, G.	119	Sun Yat-Sen University	104	Indian	50

Common keyword analysis

To identify several key themes in research on service recovery, we conducted a keyword co-occurrence analysis on keywords submitted by authors. Our main focus was to provide an overview of research in the field of service recovery. The authors in the sample examined used a total of 757 different keywords. It consists of 55 clusters of words. In the keyword co-occurrence network, the frequency of a keyword indicates the frequency of occurrence of that word. The top ten of these keywords with the highest total link strength are presented in Table 4. The keywords in the first three rows, namely service recovery, service failure, sustainability and service recovery performance, are considered to be common and more closely related keywords used in studies.

Table 4. Top ten keyword total link strength.

No	Keyword	Publication Number	Total Link Strength
1	Service Recovery	112	495
2	Service Failure	54	228
3	Service Recovery Performance	20	87
4	Customer Satisfaction	18	76
5	Hotel Employees	13	58
6	Hotels	11	50
7	Perceived Justice	9	45
8	Service Quality	9	45
9	Hospitality	8	40
10	Loyalty	8	40

Figure 2 presents the total link strength for 757 keywords. The sizes of the nodes in the shapes resulting from the analysis in the Wosviewer program show their frequency of occurrence. The curves and lines between the nodes indicate the use of words together in the same publication. The shorter the distance between two nodes, the higher the number of times two keywords co-occur [11]. The service recovery title was seen at a high rate in the search criteria because it must be visible in one of the title, abstract, keyword and keyword plus.

Co-Cited References Network

In order to strengthen the relationship network in the formation of the number of clusters during the mapping phase, the minimum number of citations of a cited reference was determined to be at least ten. As a result of the analysis, 5 clusters consist of 166 articles. However, 10 articles in the clusters were removed from the data group as a result of being marked as undefined data. 5 clusters consisting of 156 articles and relevant authors were obtained. Figure 3 visualizes the network of co-cited references. The article by Smith, A.K.; Bolton, R.N. and Wagner, J.A *Model of Customer Satisfaction with Service Encounters Involving Failure and Recovery* [13] ranks first with 109 citations. In second place, with 80 citations, is the article by Tax, S.S., Brown, S.W. and Chandrashekaran, M. *Customer Evaluations of Service Complaint Experiences: Implications For Relationship Marketing* [14], and in third place, with 72 citations, the article by Bitner, M.J., Booms, B.H. and Tetreault, M.S. *The Service Encounter: Diagnosing Favorable and Unfavorable Incidents* [15].

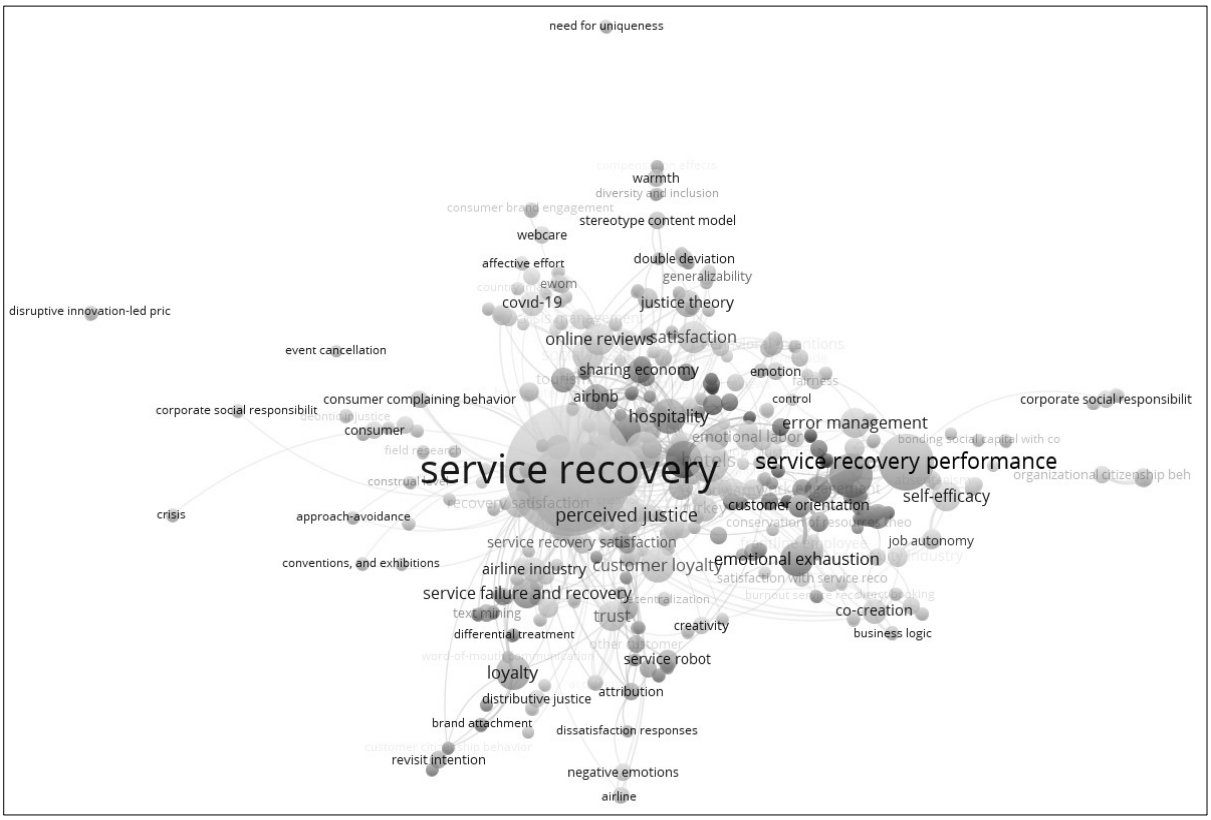

Figure 2. Keyword total link strength analysis of studies.

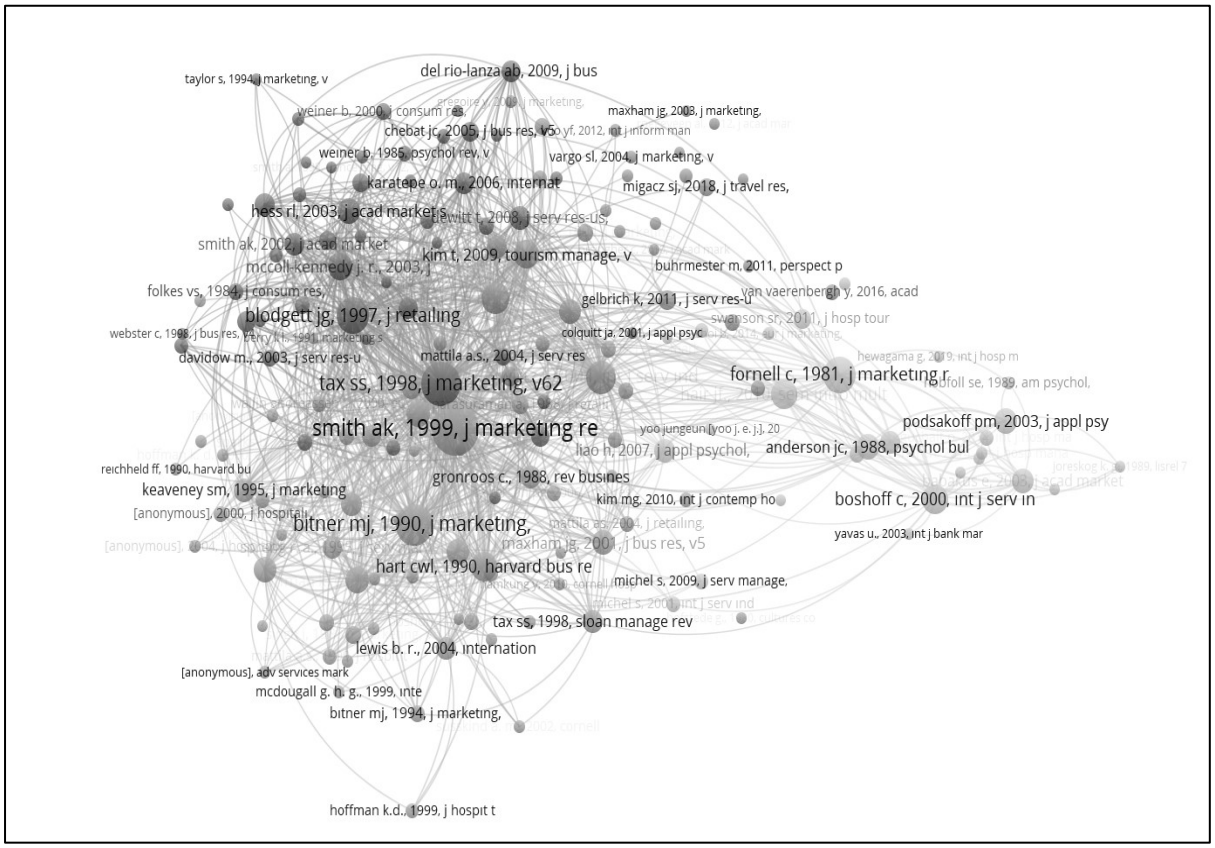

Figure 3. Network of commonly cited references.

Clusters of Commonly Cited References

The cluster names created at this stage were formed as a result of the research authors' in-depth examination of the articles in the clusters, Figure 2. Researchers created cluster titles by taking into account the topics covered in the relevant articles and the frequencies of the keywords. Table 5 presents the cluster table of commonly cited references. In the table where 156 articles are divided into five clusters, the first cluster consists of (45); Perceived Justice and Emotional Responses, second cluster consists of (32); Effectiveness of Service Recovery, third cluster consists of (32); Service Failure and Recovery Efforts, cluster four consists of (27); Customer Satisfaction and Service Recovery Performance, cluster five consists of (20); Service Problems, Customer Behavior and Service Recovery Strategies. Explanations about the headings in the table are summarized further in the text.

Cluster 1: Perceived Justice and Emotional Responses

The Perceived Justice cluster is determined as the largest cluster with 45 numbers of references. Building on the foundations of equity theory [16], social psychology and organizational behavior literature suggests that individuals involved in conflicts or disagreements base their perceptions of justice on various factors [17]. Perceived service justice is examined in three dimensions: distributive, procedural and interactional justice [18]. Distributive justice in case a consumer complains about the service provided; It includes issues such as exchange, return and discount. Procedural justice; While it expresses the arrangements regarding the repayment time of the recovery, it includes factors such as interactional justice, communication process and courtesy [19]. This theory is closely related to service failures and recovery. It is shown in this study that the three dimensions of service justice have a positive impact on service recovery [20]. This result shows that although customers experience service failure during the customer's service experience, the correct handling of the specific problem leads to customer satisfaction [21]. A quick recovery process without causing any additional difficulty to the customer is evaluated fairly by the consumer [22]. Some studies show that perceived justice has an important effect on complainants' re-behavioral intentions and negative word-of-mouth behavior. These perceptions can shape a person's re-behavioral intentions. That is, if a person feels that he/she has been treated unfairly, this may affect his/her future behavior [14, 17, 23].

Table 5. Cluster table of commonly cited references. List of references underlying number of co-titations is in alphabetical order. Full references are ommitted for clarity.

Cluster		Label	Number of co-citations in references cited
No.	Size		
1	45	Perceived Justice and Emotional Responses	10, 12, 11, 10, 14, 60, 11, 11, 28, 23, 18, 10, 10, 12, 15, 18, 14, 25, 30, 18, 20, 24, 15, 34, 12, 14, 11, 25, 10, 19, 37, 24, 21, 13, 13, 10, 27, 18, 26, 80, 10, 10, 17, 10, 15.
2	32	Effectiveness of Service Recovery	11, 11, 17, 18, 72, 18, 27, 43, 35, 12, 14, 10, 30, 17, 34, 28, 10, 29, 16, 32, 35, 12, 33, 11, 20, 11, 25, 109, 25, 12, 12, 12.
3	32	Service Failure and Recovery Efforts	10, 12, 15, 12, 12, 23, 11, 31, 16, 39, 17, 11, 12, 14, 27, 10, 46, 19, 19, 16, 10, 10, 16, 10, 12, 16, 14, 12, 18, 51, 10.
4	27	Customer Satisfaction and Service Recovery Performance	33, 10, 31, 27, 17, 43, 11, 12, 59, 15, 43, 12, 10, 12, 10, 10, 10, 30, 11, 15, 16, 10, 14, 34, 22, 10, 10.
5	20	Service problems, Customer Behavior and Service Recovery Strategies.	12, 11, 10, 14, 14, 16, 11, 15, 10, 13, 11, 15, 15, 12, 10, 19, 11, 28, 15, 13.

Cluster 2: Effectiveness of Service Recovery

The term 'recovery' in the service context is derived from British Airways' "Putting the Customer First Campaign". Service recovery is defined as the effort made by the business to recovery for the service failure or the negative effects of the failure [24]. Service recovery satisfaction expresses the extent to which a customer is satisfied with the company's efforts to correct that failure after a service failure occurs [25]. The term has recently been defined more proactively as the process of investigating service failures and dealing with these problems effectively [24]. Service recovery dimensions developed by Bosshoff [25]. consist of communication, authorization, feedback, recovery, explanation and concrete elements. Research on service recovery has concluded that recovery has a positive impact on customer satisfaction and loyalty [26-28]. Additionally, research reveals that consumers have a positive tendency to share their experiences with businesses that effectively provide service recovery [29, 30].

Cluster 3: Service Failure and Recovery Efforts

Considering the frequent occurrence of service failures in customer service and the fact that customers can be dissatisfied due to a single service failure, improving service quality is considered by both researchers and managers as a key priority for customer service strategies.

Service failure is defined as any failure, misunderstanding, deficiency or problem that occurs during the delivery of a service and causes delays or obstacles in meeting customer needs [31]. The factors that cause this situation arise from product-related personnel behavior that may arise during service delivery, attitudes and behaviors of other customers, problems experienced with the facility, or a combination of these [32]. Dealing with service failure can increase customer satisfaction and strengthen customers' intention to revisit. However, corrections to service failures must be made fairly and effectively. Wirtz and Mattila [33]. found in their study that a delayed service recovery makes the cause of service failure on consumers more stable and more controllable, and immediate recovery reduces such effects. Therefore, it emphasizes that businesses should review their processes for recovering for service failures and create positive customer experiences by providing fast and effective solutions to customers. If customer complaints are not taken seriously, failures are not fixed, or the customer is not treated fairly, customer satisfaction may decrease. As a result, it may lead to the spread of negative experiences (WOM) among customers and a decrease in the intention to revisit [34]. Therefore, it is important to adopt a fair, effective and customer-focused approach to dealing with service failures [35].

Cluster 4: Customer Satisfaction and Service Recovery Performance

Marketing-driven service recovery has a central focus on the satisfaction and maintenance of loyalty of individual customers after a service failure. Businesses focus less on satisfying and saving individual customers, and more on balancing overall performance measures by optimizing service processes [36]. Michel's study [37] reveals that recovery after service failure has a significant impact on customer satisfaction. This study shows that an accurate and effective recovery process plays a critical role in directing customers' reactions to service failures. Appropriate and timely recovery offered to customers after service failures can increase customer satisfaction, recover negative experiences, and strengthen customer relationships [38]. This emphasizes that companies should focus on effective recovery processes to strengthen their customer-oriented strategies and maximize customer satisfaction [39].

Cluster 5: Service Problems, Customer Behavior and Service Recovery Strategies

Consumer dissatisfaction and complaints are receiving increasing attention both in the tourism industry and by researchers [40]. Customer complaints generally arise as a result of an unsatisfactory purchasing experience [41]. Customer complaints are important for businesses. It is because if customer complaints cannot be handled effectively, this can increase disappointment, strengthen negative consumer reactions, and cause a decrease in the business image [40]. On the other hand, effectively handling customer complaints and improving service can turn angry and frustrated customers into loyal customers [42]. Therefore, responding sensitively to consumer complaints should be considered as an important strategy to increase customer satisfaction, minimize negative effects and create positive customer experiences [40]. After the complaint is initiated, businesses should understand the customer's perceptions and expectations and facilitate the negotiation of a solution that will provide mutual satisfaction [43]. Customer reactions to service failures are often not limited to complaints directed directly at the service provider. In such cases, customers may also convey their dissatisfaction with the service provider to others through word-of-mouth communication or seek help by telling the issue to a third party [44]. As Sparks and Browning [41] note, by exhibiting these types of behaviors, customers may share their dissatisfaction, share their experiences with other people, and seek external help to solve their problems or seek support. Therefore, service providers should strive to improve service quality and ensure customer satisfaction by taking customer feedback into account.

GAPS IN LITERATURE AND RECOMMENDATIONS

METHODOLOGICAL NOVELTY

It is observed that most studies in the reviewed literature use similar analysis methods. In the research, it was determined that the studies in all clusters generally carried out analyzes using models on service recovery. Especially in the studies in Cluster-2 and Cluster-3, it was observed that service recovery generally focused on intermediary roles. In Cluster-1, it was revealed that model studies were frequently used in service justice perception studies, which are the premise of service recovery, and a new analysis method was not applied. Some studies in Cluster-4 included service recovery in the analyzes as an independent variable. In the studies examined, it was observed that structural equation applications were generally preferred. However, the fact that articles in the clustering process are the main basis of research shows that a new analysis method has not been developed yet. In this context, it is important for future researchers to turn not only to quantitative analysis methods but also to scenario-based research. This approach can help avoid duplication in existing literature and obtain deeper understandings.

New Themes for Service Recovery Tourism Research

Studies on service recovery in the field of tourism are generally limited and mostly focused on evaluating errors in hotels and restaurants. Digital service recovery, especially within the framework of reputation management, can be considered an innovative method to increase customer satisfaction. Additionally, addressing legal aspects in studies can contribute to different sectors. Given that the majority of existing studies focus on customers, more research is needed on the impact of service recovery on managers and its direct relationship with customer retention in businesses. Research in this field can contribute to the sustainable success of businesses by explaining the importance of service recovery to managers. In this context, it is important to focus on more innovative research in future studies that will provide a broad perspective on service recovery in the tourism sector, especially including digital service

recovery and legal dimensions. This can help businesses in the industry develop more effective strategies and strengthen customer relationships.

New Directions for Service Recovery Tourism Research

It is extremely important for new researchers to conduct more in-depth research to better understand service recovery. Today, the development of technology, understanding the digital roles of service recovery and studies on how these tools can improve communication and solution processes will offer a new perspective on service recovery. Comprehensive studies involving stakeholders in the service sector such as hotels, airlines, food and beverage businesses, and package tours play an important role in understanding the results to be obtained in other service branches. These studies can reveal improvement potentials in the sector by examining how various stakeholders in the sector perceive service recovery and how these recovery activities affect customer satisfaction and experience. Additionally, studies on managers contribute to looking at service recovery from a different perspective. Issues such as the role of managers in this process, decision-making mechanisms, and customer-oriented strategies are important to ensure effective management of service recovery. Researchers and practitioners of service recovery can make discoveries in these and similar areas in order to contribute to the continued evolution of service recovery in the tourism sector. These efforts can help develop more effective and sustainable recovery strategies across the service sector.

DISCUSSION

In the literature, it is seen that bibliometric research conducted within the scope of service recovery has been examined by various disciplines. This study aims to eliminate the gap in this field by examining the concept of service recovery in the field of tourism with bibliometric technique.

RECOGNIZES KEY CONTRIBUTORS AND PRESTIGIOUS ARTICLES

We applied bibliometrics to answer the first research question, which aims to identify greater contributors to service recovery research within the specified field range. It can be seen that Guchait, P. ranks first as the prominent author in Tables 1-3. Considering the institutions, Pennsylvania State University according to Table 1 and Table 2, and Houston University according to Table 3 are the most valuable contributors. The first order of the ranking on a country basis has not changed. As seen in Tables 1-3, the USA is the country that makes the most effective contribution. Table 4 shows us that “service recovery” was the most used word by the authors compared to other keywords. A network of co-cited references helped us perform cluster analysis. In-depth evaluation and meticulous filtering of keywords in creating the cluster names of the articles divided into five clusters enabled the clustering process to occur. In this way, a guide has been designed for researchers who will work within the scope of service recovery, including specific topic headings and resources to access on these topics.

IDENTIFICATION OF THEMATIC AREAS

Service recovery is a multidisciplinary field of knowledge that includes all sub classifications of the service industry. Service failures arising from the characteristic features of services require service recovery practices when they occur in businesses. In this context, it is important that we consider the citation references that researchers commonly use in their articles, as these studies form the basis of service recovery. Instead of focusing only on tourism studies, we took into account the themes that emerged during the clustering process in order to provide a broad perspective. These themes will help us provide a more comprehensive understanding by expanding the scope of research.

FUTURE RESEARCH SCOPE

This subsection identifies potential research avenues by addressing the gaps identified in the study. Table 6 provides an overview and preliminary research questions to inspire further scientific research in the field.

Table 6. Areas of future research.

Thematic Areas	Research Gaps	Proposed Research Questions for Future Research
1. Managers' perceptions of service recovery	Most of the research has been conducted on customers, manager perceptions remain limited.	How do managers react to customer complaints and service failures, and what role do perceptions of service recovery strategies play in their reactions?
2. Digital Service Recovery: Innovative Approaches for Customer Satisfaction on Online Platforms	The studies carried out mostly include various activities carried out to satisfy customers and regain their trust in cases of customer dissatisfaction or service failure. Issues such as reputation management have not been covered sufficiently.	How effective are digital service recovery strategies (e.g., live chat support, social media assistance, automated refund systems) compared to traditional methods at increasing customer satisfaction? How can digital service recovery respond to customers' complaints more quickly and effectively?
3. Sustainable Service Recovery: Methods	In the relevant studies, issues related to the sustainable nature of service recovery have not been addressed. The concepts of sustainability and service recovery are not applied together.	How can service recovery practices in tourism businesses be improved and made sustainable? How do service recovery strategies contribute to the protection of sustainable natural and cultural resources?
4. Service Recovery in Tourism: Legal Framework, Rights and Responsibilities	There have not been sufficient studies on service recovery in tourism and the legal rights and responsibilities that customers can obtain information about in case of defective service.	Beyond simple service defects in the tourism sector, what are the legal rights and consumer protection mechanisms that can be applied in case of service failures that can be described as a breach of contract? Can alternative dispute methods be developed that can respond to consumers' legal demands quickly and less costly? What are the national and international legal standards and legislation regarding service recovery practices and how can tourism businesses comply with these standards?

Future Research 1: Manager Perceptions Towards Service Recovery

Service recovery is an important strategy to increase customer satisfaction, correct negative experiences and ensure customer loyalty [45]. Managers play a key role in these processes

because they have a direct impact on customer satisfaction and company reputation. When faced with negative customer experiences, it is vital that managers react quickly, effectively and appropriately. In addition, managers' responsibilities include improving processes by carefully evaluating customer feedback, training employees correctly, and creating effective recovery strategies that will ensure customer satisfaction [46]. In the study conducted by Armistead et al. [47] it was determined that managers perceived that service recovery processes were of critical importance for businesses and generally thought that they had a direct relationship with customer retention. For a successful service recovery strategy, determined and consistent leadership of the top management plays an important role by increasing employee motivation, ensuring customer satisfaction and strengthening the company's reputation [48].

Future Research 2: Digital Service Recovery: Innovative Approaches for Customer Satisfaction on Online Platforms

The tourism industry has entered into a transformation in recent years with the development of digital technologies. In this context, the digital age creates a change in tourists' travel, accommodation, guidance and gastronomy experiences. Thanks to smartphones, social media and other digital platforms, tourists can easily plan their travels [49]. Many service companies have understood the importance of social media platforms and started using these platforms for customer interface. Social media has become an easy, collaborative and fast platform to express complaints, especially with the widespread use of smartphones [50]. From a managerial perspective, service improvement has become crucial in maintaining excellent emotional connection with customers, especially in the rapidly changing digital environment; because online platforms (such as Agoda, Expedia and Trivago) provide a platform for customers to share their experiences, comments and experiences [51]. Social media platforms can be used as an important tool for hotels to develop effective strategies to deal with service failures and increase customer satisfaction. Hotel managers should use social media as a way to recover service failures to ensure that customers respond positively to hotels' failure solutions [52].

Future Research 3: Sustainable Service Recovery

In the tourism sector, sustainable service recovery is considered a key enabler of creating long-term customer loyalty and positive company reputation, beyond increasing customer satisfaction. To ensure the permanence of this process, tourism employees should be given regular training on customer satisfaction and service recovery. These trainings can facilitate the problem-solving process by making them more sensitive to the needs of both employees and customers. Additionally, teamwork practices to improve communication skills can strengthen staff skills. This can contribute to increased positive customer experiences. Customer feedback should be evaluated regularly and appropriate rapid responses should be given to this feedback. Customer complaints and demands should be constantly taken into consideration and service recovery strategies should be updated regularly. Personal, creative and fast solutions should be developed in accordance with these strategies. For example, technological solutions such as smart booking systems and mobile applications can support effective service recovery processes.

Future Research 4: Legal Framework

If the issue is examined from a legal perspective, there is a need to make a clear distinction between simple service failures and significant defective service issues that can be described as breach of contract. A contractual relationship – whether written or not – is established between the consumer who pays a certain fee to receive service from a tourism business and the business. However, if the services undertaken to be provided are incomplete or defective, the legal liability of the business may arise. The important point here is that objective criteria

shall be taken as basis in evaluating the service. If the service is defective or incomplete, there are legal remedies that consumers can apply. The consumer may request a refund, annulment of the contract, a reduction in the fee in proportion to the defect, or a re-visit of the service. Consumers generally exercise their rights before mediators or arbitration committees or courts authorized to resolve consumer disputes. An effective and rapid trial will both enable consumers to recovery for the damage they have suffered as soon as possible and will encourage companies operating in the field of tourism to improve their operations in order to avoid liability for recovery.

CONCLUSION

The data required to use the bibliometric method in the applied study was drawn from the WoS database and covers articles in a specific field of study. From this perspective, it can be seen that the research does not cover all data collection sources and study areas. However, research on service recovery in the hospitality, entertainment, sports and tourism categories provides an important framework in which strategies and practices in this field are examined. Therefore, these articles can be considered a rich resource for researchers and business professionals who desire to understand and improve service recovery practices in the tourism sector. In fact, while the year-based course of the study within the subject heading provides important evidence for grading the interest in the concept, the citation networks formed for the publications and the numerical results of the articles according to their place of publication are also considered to be valuable for researchers. Especially according to the frequency of citation (Table 3), it can be seen that the work of Boshoff [46], who is a pioneer in the development of the service recovery, comes to the fore in studies on service recovery. The study conducted by Blodgett et al. [17], is important as a basic source examining the relationship between customer complaints, perceived service fairness and negative word-of-mouth behavior. Additionally, the study conducted by Maxham and Netemeyer [30], is an important research that measures how service failures and recovery of such failures affect customer behavior. These studies have emphasized the critical importance of correctly recovering of service failures in order to increase customer satisfaction and prevent customer loss. Later, studies conducted by Mattila [28], examined how businesses can effectively use service recovery. These studies offer important perspectives on how businesses can develop strategies to correct and recover service failures in order to strengthen customer relationships and increase customer loyalty.

PRACTICAL IMPLICATIONS

Practical implications first, for organizations and managers new to the field, this work provides a foundation for understanding the complex dynamics of service improvement and implementing evidence-based strategies in their operations. In addition, specific clusters created within the scope of co-citation relationships and the labels that represent them serve as resources for stakeholders who want to obtain information on this subject. Offering recovery to customers quickly and effectively can increase customer satisfaction and create positive behavioural intentions. This concept plays an important role in understanding how customers react to service failures and how these reactions affect their future behavior. Resolving these failures fairly and quickly will positively impact the customer experience. It is important for companies to focus on effective recovery processes to strengthen their customer-focused strategies.

MANAGERIAL IMPLICATIONS

In addition to the data obtained as a result of the analyzes carried out in the study, what new ideas can be put forward on the concept of service recovery are discussed. Manager perceptions regarding service recovery constitute an indispensable place especially in modern management approaches. Managers are responsible for ensuring customer satisfaction with rapid and

effective reactions. They must improve processes by taking into account customer feedback, train employees properly, and create effective recovery strategies. Determined leadership of top management increases employee motivation, ensures customer satisfaction and strengthens the company's reputation. Therefore, the leadership role of managers is critical for an effective service recovery strategy. Another issue, digital service recovery, attracts attention as an innovative approach. At this point, tourism is experiencing a great change with digital technologies. Tourists can communicate effectively in travel planning and sharing experiences through smartphones and social media. Service companies, especially hotel managers, can use social media as an effective tool to address service failures and increase customer satisfaction.

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Bibliometric studies include references that are retroactive and not representative of the whole field. These articles were downloaded using the WoS database in October 2023. With the development of information technology, service recovery will tend to shift to different methods in the coming years. However, even if it changes, it has the potential to form the basis of the studies. This article provides a comprehensive overview of the field of service recovery in the tourism sector and provides a conceptual framework. The articles are drawn from the WoS database and include existing knowledge in this area. This provides a basis for future research and has the potential to support new developments in service recovery. It is expected that future research will emphasize digital service recovery more, especially at a time when digital service recovery is gaining importance in the tourism industry and studies in this direction are increasing. This trend may open new doors in the theoretical explanations of service recovery and represent an exciting future in the field. Therefore, future research is likely to add a new dimension to the field and lead to different theoretical explanations, taking into account the current trends and digital transformation in service recovery in the tourism sector.

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FACTORS AFFECTING THE ADOPTION OF SELF-DRIVING CARS

Dalma Zilahy* and Gyula Mester

Óbuda University, Doctoral School on Safety and Security Sciences
Budapest, Hungary

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ABSTRACT

Automated vehicle acceptance is being promoted by linking it to improving road safety, minimising congestion, reducing emissions and, most importantly, fatalities. However, the acceptance of Self-Driving Car users is also mainly concerned with the security of their data, the processing of tragedies reported in the media, and the moral and legal programming of the vehicle and its association with their own value system. As long as personal experience is lacking, there is no clear data protection regulation and moral programming is vague, the acceptance of Self-Driving is also influenced by the imagination of the user.

KEY WORDS

self-driving cars, improving adoption, cybersecurity, media impact, ethics

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*Corresponding author, η: zilahy.dalma@gmail.com.hu; +36204767722
Óbuda University, Bécsi út 96/B, H – 1034 Budapest, Hungary

INTRODUCTION

Recently, significant advances in machine learning and optimisation algorithms have enabled researchers to extract valuable knowledge from multidimensional data sets. Machine learning models can be trained on large datasets from the literature or databases, but their performance is often hampered by negative results or lack of metadata. In fact, by summarising metadata, we could obtain a much larger amount of data of much higher quality, and with open data management, this data could be used by the research community to reproduce experiments, perform deeper analysis or provide a basis for further studies. Accordingly, high-quality open data sets increase the accessibility and reproducibility of science [1-3].

Self-Driving Cars, as information-gathering systems, are able to collect a wealth of information about their surroundings as they travel along the route, which is of enormous value for traffic control in the long term, but for the human user, this data, even personal data, can seem daunting and unpredictable [4, 5].

ADOPTING SELF-MANAGEMENT FOR CYBERSECURITY

When Self-Driving Cars first emerged, studies showed that individuals with health problems could be unduly exposed to the stresses of Self-Driving Cars. In autonomous vehicle simulations, psychophysiological stress was indexed by skin conductance and trapezius muscle tension. Results showed that users showed more signs of physiological stress when the vehicle was autonomously driven. The results also indicated that stress increased when the passenger reported low confidence in the autonomous vehicle based on a prerecorded questionnaire. These results suggested that health professionals and manufacturers need to be aware of the physiological impact of self-driving technology on humans [6-9].

In order to reduce stern reactions, the vehicle must be both controllable and accountable. The public should also be made aware of the ways in which a self-driving vehicle can be attacked and what the user of the vehicle can do in this night. People must not feel that they are completely at the mercy of the vehicle in the event of an attack. There must be a way for the passenger to stop the vehicle, to immobilise it in the event of an emergency.

Today, it is no longer a question of how many miles the car has driven without incident, but under what circumstances it has done so. One company CEO's metric was 'miles per shutdown', where a shutdown is a moment of system failure. The number of fatalities per mile may be one such figure, but how many people are we letting die at the hands of machines in the interests of technological progress? How will vehicles calculate the movement of balloons, ducks, wheelchairs, pedestrians or animals? What does it mean for a technology to work? What exactly does safety mean to whom? How will safety be measured? Research has concluded that basic perception mechanisms need to be taken into account when designing Self-Driving Cars, which cannot simply be used as living rooms, offices or entertainment venues on wheels [10, 11].

In order to ensure effective control of the data generated, retrieved and used by Self Driving Cars, it is necessary to clearly define what constitutes basic vehicle data. If it contains personal and private data, it should be anonymised, aggregated and secured as far as possible to protect the privacy of drivers, passengers and other road users. Even if the data are not sensitive, they should be protected so that they cannot be retrieved, stored or used without the consent of the data subjects.

Governments need to effectively embed the principles of the GDPR into the car industry to effectively reassure citizens that their personal data is protected, even when using Self Driving Cars. A cornerstone of this is whether this data can be used for advertising, personalised pricing or to sell additional products to the customer [12].

The owner of the car should be informed about the processing of the data, so that he or she can make a statement about their future use.

Legal anomalies arise when Self Driving Cars are used for malicious, illegal and fraudulent purposes. Self Driving Cars can endanger the safety of passengers, pedestrians and cities if they are controlled or hacked by criminals or terrorists. Police authorities should be allowed to identify illegal Self Driving Cars activity, as long as it does not violate the privacy of innocent citizens [13-15].

ETHICAL, MORAL AND LEGAL ASPECTS OF THE ADOPTION OF SELF-DRIVING CARS

The ethics of AI must also be considered in the context of the culture, ideology and public opinion of the country, considering the social differences between collectivist and individualist principles. Future research should provide a comprehensive picture of the moral and ethical issues related to Self-Driving Cars and road safety [16].

Confidence in AI-based systems should be increased by informing users in advance about the moral and ethical values on which self-driving vehicles base their decisions. Passengers need to be prepared for situations where they would perceive a situation differently from the self-driving car and therefore make a different decision, but once comprehensive legislation is in place, the algorithm will take this into account.

Car sharing is also mainly organised along ethical and moral principles, future research should look at the barriers to the use of shared electric vehicles, including financial, technological, linguistic and cultural barriers.

PROGRAMMING ON A MORAL BASIS

One of the most difficult challenges in artificial intelligence is how to build ethical autonomous machines, as we will soon be giving millions of vehicles autonomy to make decisions. The field of experimental ethics can provide key insights into the moral, cultural and legal norms people expect from algorithms in Self-Driving Cars.

As a first step, we should decide as a community what we consider right or wrong, so that in the future, machines – unlike humans – will infallibly follow accepted moral preference.

The next step is to formulate a social framework agreement, a set of standards, which will provide clear guidelines on who is responsible for different types of accidents, how control and enforcement will be carried out in the case of Self-Driving Cars.

Consideration of ethical strategies is also a major dilemma for manufacturers. The self-protection strategy – the car protects its occupants – may offend the public, while the utilitarian strategy – the car saves as many lives as possible – may discourage consumers. To gain trust, people need to accept that there will be accidents caused by Self-Driving Cars, but for the long-term safety of transport, we need to expect them. Closely linked to this issue are hacking, liability and labour displacement, which further complicate social, legal and economic regulation.

In an ethical dilemma, it is necessary to take into the account the needs, preferences and possibly conflicting goals of the participants, as well as their personal and social context. AI systems are becoming more and more autonomous, the number of possible situations, choices and influences on their actions is growing exponentially, but it would be necessary to integrate some kind of “ethical sensor” into autonomous systems [16].

Attempts to define ethical principles have therefore recently surged across the world. Scientific and technological organisations have set up AI governance committees, which publish principles for the governance of AI.

The principles emphasise that the development of AI should be driven first and foremost by the enhancement of the common welfare of humanity. Human rights, respect for privacy, fairness, transparency – which are the operating principles of AI – accountability – accountability in both the development and deployment of AI systems – the importance of collaboration and agility to manage new and emerging risks was also highlighted.

The principle of consistency of rights and responsibilities emphasises the need for data to be properly captured and monitored, while commercial entities must be able to protect their intellectual property. In the private sector, one of the most emphatic ethical frameworks comes from Tencent CEO Pony Ma. This framework emphasises the importance of AI being accessible, trustworthy, understandable and verifiable.

RIGHTS

Policy makers have found that while Self-Driving Cars offer the possibility for more people to use them (e.g. elderly, disabled and blind people), there is also a challenge in who to deny the right to use them.

However, over the years we have slowly come to the point where we should ban non-autonomous driving when we reach a stage where Self-Driving Cars can safely and easily replace non-autonomous driving. US and UK road safety authorities have indicated that this is inevitable in the next 50 years. Meanwhile, groups such as Humans Against Autonomous Vehicles (HAAV) are strongly opposed to Self-Driving Cars as not safe enough to drive.

AUTONOMY

Autonomy can also be compromised in AV, with a loss of choice and control in car navigation. In China there have been cases where the vehicle has taken control from the driver in non-automated mode. The feeling of freedom to drive will also change, because Self-Driving Cars are programmed to obey speed limits and road conditions, so the freedom to drive will be lost. In other cases, Self-Driving Cars have been programmed to obey speed limits and road rules, so the freedom to drive has been removed. In California, a pregnant woman went into labour and had to be transported to the hospital, but the Self-Driving Cars speed limit regulation caused significant delays, almost causing damage to the newborn's brain capacity.

RESPONSIBILITY

The tendency for owners of autonomous vehicles to shift the responsibility to themselves and to be exempted from liability by driving in autonomous mode may be a cause for concern.

INSURANCE AND DISCRIMINATION

Cars can interrogate a wide range of driving habits, patterns and behaviours, so if insurance companies have access to this information, they can tailor insurance policies to individuals' driving performance. Insurance companies defend this as a way to offer better insurance premiums to safer drivers, but access to this data violates people's right to privacy by creating a sense of constant surveillance inside the vehicle.

Owners of manual cars have rejected Self-Driving Cars precisely because of the insurance imbalance – because insurance companies offer more favourable terms to Self-Driving Car drivers who allow their data to be monitored.

SELF-DRIVING AND THE IMPACT OF MEDIA

Positive media coverage significantly increases people's confidence and willingness to use driverless cars. The media influence self-efficacy and subjective norms and thus change

people's confidence and behaviour. People are more willing to accept driverless cars. In order to promote self-driving cars, individuals need to trust the mechanisms more than themselves, which is a self-awareness challenge.

Therefore, in the future, energy should be devoted to comparing human driving capabilities with those of self-driving vehicles, and to clearly inform users about the functions in which the machine outperforms human cognitive capacity, the way in which it makes decisions and the situations it handles differently from a human driver.

Mass media is increasing consumer perception bias with reports of accidents, injuries and deaths involving self-driving cars. The potential impacts of autonomous vehicles on urban tourism, which have captured the imagination of the media and the public, are linked to unrelated opportunities and concerns such as sex, recreation, illegal work, and terrorism and tourism. This suggests that the media and the public experience autonomous vehicles not necessarily through the lens of inevitability and a desire for transport efficiency, but rather by linking them to uncertainties whose effects have the potential to both promote and hinder economic life.

It is therefore important to make people aware not only of the anomalies of self-driving cars, but also of the potential for abuse, which could lead to misuse of the vehicle, and to separate the negative effects of possible abuse from the benefits of self-driving.

Already, research published in 2018 has alerted car manufacturers that people are more accepting of self-driving vehicles after they have used prototypes, with early personal experiences with prototypes less likely to influence later use. User interface design will play an important role in the introduction of Level 2 and Level 3 self-driving vehicles.

However, it should be noted in relation to research on Tweeter data that algorithms measuring it can discriminate very well. In this context, a separate discipline has emerged and developed the concept of "algorithmic correctness". Racial and gender groups are most affected by algorithmic fairness because they are most often harmed by algorithmic inequalities. If our demographic characteristics predict how we should behave, then algorithm designers need to be more demographically sensitive and representative if they are to reflect the population as a whole.

Therefore, race, ethnicity, religion and gender should be carefully addressed with all target groups, so that self-driving vehicles are not accused of being the "fad" of white, higher-educated, technologically savvy men.

Excessive media coverage of rare accidents will trigger a distorted perception of passenger risk, which may irrationally overshadow the greater safety benefits. In the future, it is essential that the media also report on situations where a self-driving car clearly performs better than a human driver. Car manufacturers should expand their marketing strategies to include information where a self-driving vehicle is clearly safer than a human driver.

AV manufacturers need to address not only production, but also how their innovations are covered by the media. For manufacturers and other stakeholders, it will be important to ensure that the public is presented with facts and not opinions influenced by media gatekeepers. Australians, for example, are more open to autonomous vehicles if they are informed about their public health benefits. A factual balance between the advantages and disadvantages of the technology needs to be provided to the public so that they can make credible decisions.

CONCLUSIONS

Automated vehicle acceptance is being promoted by linking it to improving road safety, minimising congestion, reducing emissions and, most importantly, fatalities. In the absence of personal experience, without a single privacy policy, the adoption of Self-Driving Cars is influenced by the user's imagination.

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SUITABILITY OF BLOCKCHAIN FOR STORING PRIVATE DATA FROM IOT DEVICES

Marija Cekuš[1,*] and János Simon[2]

[1]Subotica Tech-College of Applied Sciences
Subotica, Serbia

[2]University of Szeged, Faculty of Engineering, Department of Mechatronics and Automation
Szeged, Hungary

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ABSTRACT

The explosive growth of Internet of Things devices over the past two decades has created pressing challenges for storing the vast amounts of data generated by connected devices. Concurrently, blockchain technology has rapidly evolved, providing new avenues for storing data securely, efficiently, and in near real-time. This article investigates the suitability of various blockchain platforms for Internet of Things data storage, selecting seven platforms – namely, IOTA, Signum, Ethereum, Solana, Polygon, Stellar, and Hyperledger Sawtooth. A comprehensive set of criteria and scoring methodology were developed to assess each platform's strengths and limitations for this use case.

Our findings identify IOTA as the most suitable platform due to its feeless transactions, high transaction throughput, and extensive data storage. Signum and Ethereum also showed potential, though with noted limitations in community support, transaction fees, and speed. Platforms like Solana, Polygon, and Stellar demonstrated effective storage capabilities on Layer 2, which introduces additional complexity and costs. The methodology developed here provides a framework for future research, suggesting that additional platforms be evaluated, the scoring criteria refined with weighted parameters, and practical validation conducted through a prototype Internet of Things system to further validate and optimize blockchain selection for Internet of Things data storage.

KEY WORDS

internet of things, blockchain, data protection

CLASSIFICATION

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*Corresponding author, η: 28122005@vts.su.ac.rs; +381 60 6669904;
Marka Oreškovića 16, 24 000 Subotica, Serbia

INTRODUCTION

The Internet of Things (IoT) has experienced substantial growth over the past two decades. In the early 2000s, IoT technology was in its early stages of development with limited application in specific industries. Since then, the global use of IoT devices has increased substantially, reaching billions of connected devices. In 2003, with a global population of approximately 6,3 billion, around 500 million devices were connected to the internet, equating to roughly 0,08 connected devices per person. The rapid growth of handheld devices dramatically increased the number of connected devices to around 12,5 billion by 2010, while the population rose to 6,8 billion, resulting in more than one connected device per person, specifically 1,84 devices per individual, Figure 1.

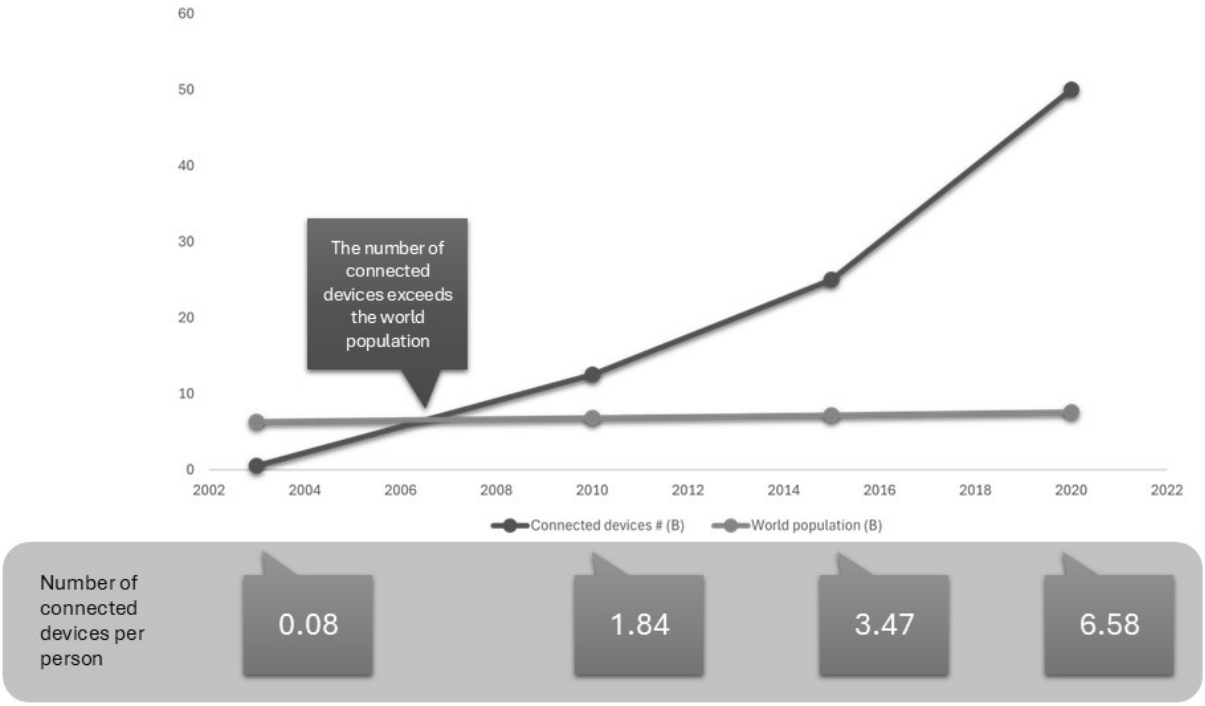

Figure 1. The growth of the world population and the number of connected devices.

Cisco's forecasts from over 10 years ago [1] predicted that the number of connected devices would reach 50 billion by 2020. Further predictions suggest that the number of connected devices will surpass 100 billion by 2050 [2].

With this pace of development, one of the challenges that will inevitably need to be addressed in the near future is the storage and protection of data generated by connected devices. Due to their design, IoT devices are not suitable for data storage in the general case, and most IoT devices lack the capacity to encrypt data on the device itself.

Blockchain technology, which is somewhat newer than IoT and has gained popularity after the emergence of Bitcoin in 2008, is also rapidly evolving. Although the original idea of Bitcoin's creator, the famous Satoshi Nakamoto, was to use blockchain for implementing a cryptographically secure peer-to-peer payment system [3], further development of this technology has introduced additional applications of blockchain in various industries such as finance, healthcare, logistics, and others [4]. It is expected that blockchain technology will continue to grow rapidly in the coming years. In addition to the need for fast, secure, and transparent transactions, the development of distributed applications (dApps) will expand the ways blockchain can be used. Some blockchain solutions already allow data storage.

RESEARCH AIM

This article investigates the suitability of currently available blockchain solutions for storing data generated by IoT devices. To achieve this, we propose a scoring methodology that evaluates key features of selected blockchains, enabling a clear assessment of each platform's appropriateness for IoT data storage. Our research is based on a comprehensive review of documentary sources, including academic papers, websites, code repositories, community documentation, and other relevant materials.

RELATED WORK

The convergence of IoT and blockchain technology has been explored from various perspectives, with researchers proposing numerous solutions for their integration across diverse use cases. Hashemi et al. [5] introduced a three-component architecture in "World of Empowered IoT Users", leveraging blockchain to securely store IoT data and provide users with direct control over data access. This decentralized framework supports applications in healthcare, smart cities, and autonomous vehicles, facilitating transparent management across multiple domains [5].

In "Survey on Blockchain for Internet of Things", Wang et al. provide an in-depth evaluation of blockchain technologies tailored to the specific needs of IoT applications. Their comparative analysis of ten blockchain platforms examines both strengths and limitations, offering insights into how factors like scalability, security, and efficiency align with IoT requirements [6].

Dai, Zheng, and Zhang [7] introduced the "Blockchain of Things" (BCoT) concept in their survey, "Blockchain for Internet of Things: A Survey". The BCoT framework merges blockchain and IoT to tackle challenges related to scalability, security, and interoperability, positioning blockchain as a key enabler of IoT network integrity and data transparency [7].

Kotel et al. [8] investigated the application of Hyperledger Fabric to enhance security in IoT-enabled smart homes. Their study, "A Blockchain-Based Approach for Secure IoT", emphasizes blockchain's decentralized architecture as a means to strengthen data integrity and user privacy, making Hyperledger Fabric a promising platform for secure IoT environments [8].

Bouras et al. propose a "Lightweight Blockchain-Based IoT Identity Management Approach" that uses a permissioned blockchain for efficient IoT identity management. Their framework emphasizes lightweight operation and high security, addressing the constraints of resource-limited IoT devices [9].

Kumar and Sharma [10] conducted a comprehensive review of trust management approaches in IoT, comparing conventional and blockchain-based techniques. Their findings, published in "Leveraging Blockchain for Ensuring Trust in IoT: A Survey", highlight blockchain's advantages in transparency and resilience over traditional methods [10].

Tseng et al. [11] examined blockchain-based databases for IoT, focusing on the Bitcoin Backbone Protocol (BBP) as a foundation. Their study, "Blockchain-Based Database in an IoT Environment: Challenges, Opportunities, and Analysis", identifies challenges and proposes a consistency mechanism that addresses scalability and reliability in IoT data management [11].

Athavale and Bansal [12] explored a framework using Hyperledger Fabric to securely manage and store IoT data. Their work emphasizes blockchain's capacity to decentralize IoT data management, addressing key issues in secure data handling [12].

Lastly, Zhao et al. [13] propose a secure storage solution for agricultural IoT data in their study. By combining RC5 encryption with blockchain, their framework enhances data confidentiality and integrity, providing a tamper-proof system for managing sensitive agricultural information [13].

ARTICLE OUTLINE

1) Introduction: This section provides the context and objectives of our research and presents a brief overview of relevant related work by other authors.
2) The Internet of Things and the Data it Generates: This section introduces the concept of IoT, reviews common applications of IoT devices, and addresses key challenges related to data privacy and security.
3) Blockchain Technology: This section explains blockchain fundamentals and highlights significant aspects of blockchain operations relevant to this study.
4) Analysis of Blockchain Suitability for Storing IoT Data: Here, we present our scoring methodology, detailing the blockchain parameters evaluated and the evaluation criteria applied.
5) Analysis of Blockchain Solutions for Storing IoT Data: This section offers a summary of seven selected blockchain platforms based on documentary research and applies our scoring methodology to assess each platform.
6) Conclusions: In the final section, we summarize the scoring results, discuss the findings, and suggest directions for future research.

THE INTERNET OF THINGS AND THE DATA IT GENERATES

IoT is a term used to denote a large group of heterogenous physical devices, embedded with sensors, software and other technologies that allow them to connect to the internet and exchange various types of data with other systems and devices over the internet. The data generated by these devices is diverse, extensive, and often requires real-time processing and storage. For certain types of IoT data, preserving privacy and confidentiality is also necessary, both at the point of generation, during transfer, and in storage. Due to the limited hardware capabilities of IoT devices, as well as the constraints of available storage space on the devices themselves, encryption and data storage on the devices is often not possible. Additionally, some IoT devices are in inaccessible areas where broadband internet or stable, uninterrupted connection cannot be guaranteed, making the secure and safe transfer of data from the device to the storage location a complex challenge.

IoT devices generate various types and formats of data, often depending on the device's purpose. Some applications of IoT devices lead to the creation of high volumes of data. The type and format of data sent by IoT devices over the network largely depend on the task performed by the IoT device, as well as its position, mode, and operation method.

For this article, the data generated by IoT devices will be grouped according to the application of the devices.

APPLICATIONS OF IOT DEVICES

IoT data is crucial for the development of smart cities, enabling efficient management of resources, traffic, and services. In smart cities, IoT devices are used to form smart grids – various measurement devices and sensors are used to measure energy consumption, availability of services, or resources. They are also used for traffic monitoring, particularly in so-called "connected vehicles", in traffic cameras, GPS devices, which track traffic flow, vehicle locations, public transportation, road conditions, and more. Part of the smart city concept is environmental monitoring, done through air quality sensors, weather stations, noise sensors, which generate data on air pollution, temperature, humidity, and noise levels. In public safety monitoring in smart cities, surveillance cameras, emergency response sensors, and gunshot detectors are used to generate data on crime rates, incidents, as well as real-time video footage.

IoT devices are used in smart buildings, where they monitor and control heating, cooling, lighting, and track human presence in certain rooms or parts of the building. In such applications, IoT devices generate data on energy usage and indoor air quality, among other things. IoT devices also play a role in waste management, where they monitor waste levels, generating data on the amounts of collected waste, waste collection regimes, and the level of recycling. With the help of IoT devices, water systems in smart cities are also monitored, including water flow rates, water consumption, detection of pipeline damage and supply interruptions, as well as water quality [14].

IoT devices have found special applications in medicine and healthcare, where they are used to monitor patients' vital parameters. IoT devices for monitoring body parameters have found widespread use – from smartwatches and fitness trackers, wearable glucose monitors, blood pressure monitors, to smart inhalers, infusion pumps, and connected implants, and sensors that monitor patient conditions in hospital beds [15].

Industrial IoT refers to the use of IoT devices in industrial environments to improve efficiency, safety, and maintenance. IoT devices in industrial environments are used for predictive maintenance – i.e., monitoring the parameters of industrial systems, such as vibrations, temperature, oil levels, wear of parts, process optimization, monitoring material flow and consumption, production speed and quality, as well as monitoring compliance with safety standards [16].

Agriculture is another field where IoT devices are used. They are tasked with monitoring soil conditions – especially parameters such as moisture, pH value, temperature, monitoring weather conditions – temperature, air humidity, precipitation, wind speed, as well as crop health and condition – growth, presence of diseases and pests, nutrient levels. IoT devices are used to control and monitor irrigation on agricultural land [17].

This, of course, is not an exhaustive and comprehensive overview of all possible applications, but merely a limited list. However, this brief overview shows that IoT devices are diverse and used in various environments for a wide range of tasks. Consequently, the data generated by IoT devices is also highly varied – from short textual data sent, through more complex structures, to photos and video materials.

SECURITY AND PRIVACY OF DATA GENERATED BY IOT DEVICES

As IoT devices become increasingly present in everyday life, from smart homes to industrial systems, the issue of privacy and security of the data these devices generate is becoming more significant. Additionally, the storage of large amounts of data generated by these devices is becoming a growing challenge.

Some of the challenges in managing data security and privacy include:

- hardware limitations of the devices themselves – IoT devices often have limited resources, such a processing power and memory, making the implementation of security protocols a challenge [18],
- heterogeneity – IoT devices use different standards and protocols, depending on device manufacturers, which introduces challenges in interoperability and security gaps [19],
- large data volume – timely analysis and detection of generated data is hampered by the large volume of data [20],
- device maintenance – IoT devices often have a long lifespan, but updating and upgrading security features is not guaranteed or regular.

To address these challenges, various measures can be implemented to protect data privacy and security, such as:

- data encryption applied during transmission and storage, to protect data integrity and prevent unauthorized access,
- authentication and authorization: if implemented using modern, secure methods, such as two-factor authentication (2FA), it allows control of access, ensuring that access to the device and data is granted only to authorized users,
- regular security updates and maintenance: by maintaining the software and firmware of IoT devices, known vulnerabilities of devices and systems on them are removed,
- security protocols such as TLS/SSL, ensure secure data transmission,
- applying machine learning techniques on generated data helps detect unusual patterns in the data that may indicate security threats [21].

BLOCKCHAIN TECHNOLOGY

Blockchain is a decentralized, cryptographically secured database shared across network participants. Although the concept dates back to 1982 [22], the first fully decentralized blockchain was implemented in 2008 with the advent of Bitcoin. Bitcoin solved the problem of double-spending and initiated the development of technology that today counts tens of thousands of blockchains with over 100 000 cryptocurrencies.

A blockchain represents a decentralized ledger of transactions. Nodes on the Bitcoin network, also referred to as miners, add validated transactions to the ledger, Figure 2. By applying mutually agreed rules of transaction validation, Bitcoin nodes build the authoritative ledger of transactions that establishes who owns what.

A blockchain can function perfectly well without cryptocurrency.

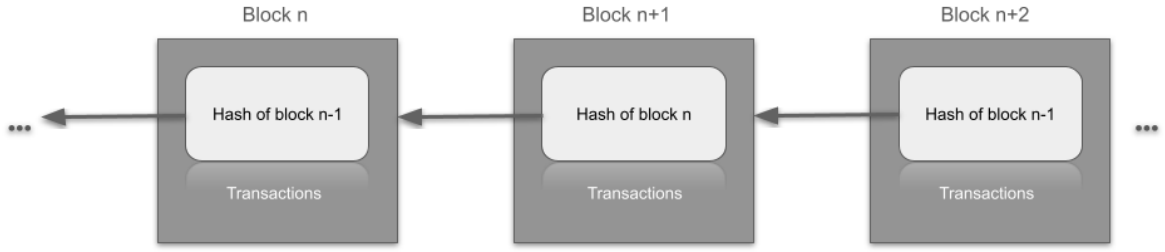

Figure 2. A schematic representation of blocks and their connections in a blockchain.

Transactions or records on the blockchain are grouped into timestamped blocks. Each block is identified by its cryptographic hash and references the hash of the previous block. This establishes a connection between blocks, creating a chain of blocks, or blockchain. Any node with access to this ordered list of linked blocks can read it and determine the state of the data exchanged on the network.

We will examine the operation of a blockchain network, in order to understand how the blockchain gets extended by new blocks. The network of a blockchain consists of nodes (clients) that each hold a copy of the database and exchange information with the blockchain. Multiple blockchain users can use a single node as an entry point, but we will assume, for simplicity, that each user issues transactions using their own node. The nodes are connected into a peer-to-peer network, where:

1) Each participant in the blockchain network holds a set of private and public keys, which they use in interactions with the blockchain. The private key signs transactions. The public key is the user's address on the network. Once a node issues a transaction and signs it, the transaction is broadcast to the network.

2) Neighboring nodes validate incoming transactions. Valid transactions are propagated further to the network, invalid transactions are discarded. This is how correct, validated transactions reach all nodes on the network.
3) Validated transactions are collected into a new block, which is proposed at regular intervals. Transactions in the proposed block are time-consumed and ordered by time. The new block is mined by a node, which propagates the block to the network. (The way the mining node is chosen, and the block content depends on the consensus mechanism the network uses.)
4) Before appending the new block to the blockchain, nodes verify transactions validity, and ensure the correct hash is referenced from the previous block. In case the block fails verification, it is discarded. If the new block is verified, the nodes apply the transactions contained in it and update the state of the blockchain. This process is repeated at regular intervals.

The blockchain network is made up of untrusted nodes, that share a database without a trusted intermediary and write data to this database. To help the network achieve a common global view (i.e. reach consensus), all blockchain networks implement a set of specific rules that every participant in the validation process must follow.

The rules applied to determine if an incoming transaction is valid, and whether it should be propagated to the network or not, are uniform for all participants in the validation process. This ensures consensus is reached without the need for trusted intermediaries.

When all nodes follow the steps described above, a blockchain becomes an authenticated and timestamped record of the activity of nodes that participate in the network. As a result, trust emerges within the blockchain from the interactions between participants in the network.

This is a fairly simplified and generalized description of how blockchain operates. Blockchain can also be used for the transfer and tracking of digital assets or for executing code [23].

TYPES OF CONSENSUSES AND HOW THEY ARE ACHIEVED

Blockchain nodes must reach consensus on the transactions and their sequence in newly generated blocks. If this consensus is not achieved, the blockchain will differ at different nodes, causing a fork in the blockchain. When nodes hold different versions of the network's global state, the unified authoritative chronology of the blockchain is disrupted, unless forks are resolved.

To address this, every blockchain network employs a distributed consensus mechanism. The specific consensus mechanism, through which the nodes continuously validate the network's state, is determined by the blockchain's architecture and design.

If all validating nodes would vote on the transaction order, and transactions receiving the majority vote would be added to the next block, a blockchain that operates in an open, public network, could be exposed to "Sybil" attacks [26], where a single participant manipulates the network by creating multiple identities to vote, potentially seizing control of the blockchain in their favor.

To handle potentially malicious participants on the network, distributed consensus mechanisms that blockchains implement require a form of "investment" – referred to as "proof" that increases the cost of the manipulation of the blockchain.

PROOF OF WORK

Bitcoin addresses the consensus issue by making block mining computationally intensive, so having multiple identities on the network does not increase the probability of mining a block. Any node on the network can propose the next block, if it computes the random number (nonce) in the block header leading to the block header's hash to have the required number of leading zeros.

The node that solves this computational puzzle produces the Proof of Work (PoW) and earns the right to create and publish the next block in the chain.

Other nodes can easily verify the provided solution and extend their copy of the blockchain with the new block, as the block header is created using a cryptographic hash function. Forks in the blockchain network can occur in rare cases when two nodes publish a new block at the same time. These forks are resolved automatically by the next block, as the PoW mechanism extends the branch with the most accumulated work. The longest chain will be accepted by the nodes, and the consensus will be restored on the correct order of transactions.

Different cryptographic hash functions, such as SHA-256, Blake-256, and scrypt are used for PoW. Some systems combine several algorithms together, like Myriad [25].

PROOF OF STAKE

Proof of Stake (PoS) is an alternative consensus mechanism, offering far lower computational demand than PoW. In blockchains that implement PoS, a node's chance of mining the next block is directly proportional to the amount of cryptocurrency staked in a wallet. Implementations of PoS can be quite intricate and come with their own set of advantages and drawbacks.

Some variations of PoS are:

- Chain-Based PoS: The validator holding the largest stake on the network creates the next block. Examples include Nxt and Peercoin,
- Byzantine Fault Tolerance (BFT) PoS: Uses delegates chosen to validate blocks, allowing faster consensus with security. Examples include Tendermint and Cosmos,
- Delegated Proof of Stake (DPoS): Users (nodes) vote for delegates who will validate transactions, achieving faster and more efficient validation. Implemented on the EOS and Tron blockchains,
- Bonded PoS: Validators "bond" or stake tokens as the right to validate blocks. If validators act dishonestly, the staked tokens can be forfeited. Examples include Cosmos and Polkadot,
- Hybrid PoS/PoW: Hybrid consensus mechanisms introduce greater security and decentralization by combining PoW and PoS, as implemented on the Decred blockchain [26].

PROOF OF SPACE OR PROOF OF CAPACITY

Proof of Space, referred to sometimes as PoC, is a consensus algorithm that leverages unused hard drive space instead of computational power or staked cryptocurrency tokens. This reduces the energy consumption required for block mining, addressing one of the common criticisms of PoW, and it is less prone to centralization compared to PoS.

PoS operates by having network participants (miners) allocate a portion of their hard drive space to store plot files, which are precomputed hashes of cryptographic functions. The larger the miner's plot file, the greater the likelihood that they will create the next block.

One of the main advantages of PoS is its energy efficiency compared to PoW, as well as the accessibility of resources – users typically already have hard drives and do not need to acquire specialized equipment as they would with PoW. However, like other consensus algorithms, PoS is not immune to centralization risks, where users with disproportionately large amounts of storage can dominate the mining process. A potential attack vector in this system is the "grinding attack" where malicious actors falsely inflate their allocated space to gain an advantage [27].

Burstcoin was one of the first blockchains to implement Proof of Space. Chia is another well-known blockchain that uses a modified version of this consensus "Proof of Space and Time" a combination that further enhances network security.

IMPLEMENTATION METHODS

The previous sections described the main concepts of consensus algorithms used in blockchain networks. It is important to note that each type of proof requires participants on the network to

possess a certain type of resource – work, stake, or space – which grants them a varying degree of likelihood to create a new block and thereby extend the blockchain.

Although blockchain technology is still in its infancy, with less than 20 years of history, some of the early weaknesses in consensus algorithms have been identified, and newer solutions often implement hybrid consensus mechanisms by combining two or more types of proofs. This is the case with Decred, for example, or the new version of Burstcoin, which has been renamed Signum, and implements a consensus algorithm that combines Proof of Space and PoS.

ANALYSIS OF BLOCKCHAIN SUITABILITY FOR STORING IOT DATA

To assess the suitability of blockchain for storing data generated by IoT devices, we will examine, compare, and evaluate the parameters of various operational blockchain solutions. It is estimated that there are currently at least 1000 different operational blockchain networks. Among them are large public blockchain networks such as Bitcoin and Ethereum, as well as specialized blockchain networks designed for specific industries or applications. Some active blockchain networks have very active communities that contribute to the promotion, development, and operation of the network.

PARAMETERS FOR EVALUATING BLOCKCHAIN SUITABILITY FOR STORING IOT DATA

In principle, many aspects of blockchain technology could be evaluated in the context of blockchain suitability for storing data from IoT devices. However, for the purposes of this article, the parameters considered are limited to:

1) Access to blockchain: private, public, limited
2) Layer on which data is stored: Layer 1, Layer 2, or higher layers,
3) Cost per transaction on the blockchain: costs will be converted to USD/tx (U.S. dollar per transaction),
4) Transaction speed on the blockchain: measured by the speed of generating new blocks and/or the speed of confirming transactions. Transaction speed will be converted to transactions per second (TPS),
5) Data storage capacity: measured by the maximum size (or length) of data that can be sent in a single transaction,
6) Existing security and data protection features,
7) Existence of a community that promotes, maintains, and develops the blockchain,
8) Complexity of implementation measured by the availability of tools, libraries, source code and documentation.

As mentioned earlier, there are dozens of parameters that can be used for comparison and evaluation in addition to the ones listed above.

EVALUATION METHODOLOGY

To store data generated by IoT devices, the optimal blockchain should possess the following characteristics:

- public access – not requiring permissions, registration, or payment to access the blockchain,
- blockchain architecture that allows storing data on Layer 1,
- low transaction cost – measured by the amount of money paid to add a transaction to the blockchain,
- fast transaction confirmations and block generation on Layer 1 – short block time and high number of TPS,

- high data storage capacity – the amount or arbitrary data that can be stored with a single transaction,
- existing security and data protection measures – libraries or built-in features that secure arbitrary data,
- active community that maintains the blockchain and its ecosystem of distributed applications, measured by the existence, availability, and activity of communication channels (social networks, platforms, repositories),
- available tools and libraries that facilitate easy integration of middleware and applications written in popular programming languages.

In Table 1 we are presenting how we evaluate the selected blockchain parameters and how we assign scores:

Table 1. Evaluation methodology.

Parameter	Score: 10	Score: 5	Score: 0
Access	Public access, with no payment or authentication	Limited access (e.g. approval-based)	Authenticated access or required payment, private blockchain
Layer for data storage	Layer 1	Layer 2	Layer 3 or higher
Price of a single transaction, USD/tx	0	< 0.01	≥ 0.01
Transaction Speed, TPS	≥ 999 (L1)	< 999 (L1); Any (L2) or configurable	N/A
Data storage capacity, Byte	> 1000	≤ 1000, unclear or configurable	N/A
Existing data security and protection features	Data security and protection features available	N/A	Data security and protection features not available
Community	> 1 million followers on social media	≤ 1 million followers on social media	N/A
Implementation complexity	Libraries available in TIOBE Top 10 programming languages [28]	Libraries available in programming languages outside TIOBE Top 10	N/A

We use scores of 10, 5 and 0 to achieve sufficient differentiation among the platforms we are analyzing. Entries in Table 1 marked as "N/A" are not used.

- Access: blockchains with free, public access that require no authentication are scored with a 10, blockchains where the access is limited by, for example invitation or approval will be scored 5. Private blockchains are scored with 0.
- Layer for data storage: if it is possible to store IoT data on Layer 1, we will assign score 10. If it is possible to store data on Layer 2 (Smart contracts) we will assign a score of 5, if data storage is possible only on Layer 3, we will assign 0. Note that we assign score based on lowest layer where data storage is possible (e.g. if it is possible to store data on Layer 1 and Layer 2, we will assign a 10).
- Price of a single transaction (USD/tx): If transactions are free (no fee), we will score the blockchain with 10, if the fee payable for execution of one transaction is less than 0.01 USD (less than 1 USD cent), we will assign a score 5, and for transaction fees equal to or above 0,01 USD, we assign a score of 0.

- Transaction speed: as stated above, we favor Layer 1 data storage possibility, and prefer high transaction speed on Layer 1. Therefore, we assign a score 10 to blockchains where the Layer 1 transaction speed is equal to or above 999 TPS, and a score 5 for blockchains with transaction speed less than 999 TPS on Layer 1. All blockchains where data storage is possible on Layer 2 or higher layers are scored with 5 for transaction speed.
- Data storage capacity (Byte): Blockchains that allow more than 1000 Byte of data to be stored with one transaction are scored 10. Blockchains where the amount of data that can be stored with one transaction is equal to or less than 1000 Byte, or where the amount of data that can be stored with one transaction is not clear (e.g. Ethereum) are scored with 5.
- Existing data security and protection features: blockchains wich allow additional data security and protection – such as encryption of arbitrary data – are assigned a score of 10. Blockchaisn that have no such features, are assigned a score 0.
- Community: if the blockchain communities on X (formerly Twitter) and Reddit have more than 1 million followers (combined) we assigned a score of 10. If the sum of two social media following is less than 1 million, we assigned a score of 5.
- Implementation complexity: as the optimal blockchain described at the beginning of this chapter will have tools and libraries that allow for easy implementation of additional tools, distributed applications and middlewares, we score the implementation complexity by the available tools and libraries that facilitate integration of other tools and interfaces. If libraries and tools are available and are written in programming languages that are in the top 10 of the TIOBE index, we assign a score of 10. If libraries, tools and SDKs are available in programming languages that are not in TIOBE top 10, we assigned a score of 5, due to the potential difficulty of finding developers who are familiar with such programming languages.

The parameter scores for each blockchain will be summed up to obtain a total score, which can have a maximum value of 80.

This way, we will rank the selected blockchains, and the one with the highest total score will be considered the most suitable for storing IoT data.

LIST OF BLOCKCHAIN SOLUTIONS FOR ANALYSIS

After preliminary research of existing blockchain solutions, we have compiled a list of 7 blockchain solutions that will be analyzed in detail. During the preliminary research, we eliminated solutions from further analysis that would certainly not meet the criteria outlined in the previous section.

The detailed analysis, following the methodology from the previous section, will be conducted on the following blockchain solutions: IOTA, Signum, Ethereum, Solana, Polygon, Stellar, and Hyperledger Sawtooth.

ANALYSIS OF BLOCKCHAIN SOLUTIONS FOR STORING IOT DATA

IOTA

History and Creators: IOTA was founded in 2015 by Sergey Ivancheglo, Serguei Popov, David Sønstebø, and Dominik Schiener. The project originated from the Jinn project, which focused on developing ternary hardware for the IoT ecosystem. After rebranding Jinn to IOTA, the first token sale was held in October 2015. IOTA was developed by the IOTA Foundation, a non-profit organization based in Berlin, Germany. The organization oversees the development and maintenance of the network and protocol.

Purpose: IOTA is designed to enable secure and efficient data exchange and payments between devices in the IoT ecosystem. Its mission is to become standard for transactions between connected devices, ensuring interoperability and security without the need for intermediaries.

Architecture: The core of the IOTA network is the Tangle, a structure based on a Directed Acyclic Graph (DAG), Figure 3. Unlike traditional blockchain systems where transactions are grouped into blocks, Tangle allows the addition of individual transactions that mutually confirm previous transactions. This enables parallel transaction confirmation without a centralized authority, eliminating miners and transaction fees, making the network more scalable and efficient.

Consensus Algorithm: IOTA uses a unique consensus approach through the Tangle. When a user initiates a new transaction, they must confirm two previous transactions on the network, ensuring validation without centralized mining. Each transaction requires minimal computational resources to solve cryptographic puzzles via PoW algorithms, preventing spam. This approach allows for fast and fee-free transaction processing.

In the latest versions, such as IOTA 2.0, additional mechanisms like Fast Probabilistic Consensus (FPC) have been introduced to enhance decentralization and security. The removal of the central Coordinator is planned through a project called Coordicide, which will allow for complete decentralization of the network [29-32].

Additional Information: WOTS (Winternitz One-Time Signatures) are quantum-resistant, ensuring the security of transactions even in a future where quantum computers are more prevalent [33], Table 2. This feature adds an additional layer of protection to IOTA's network, making it resilient against emerging technological threats, which is particularly important for long-term data security in the IoT ecosystem.

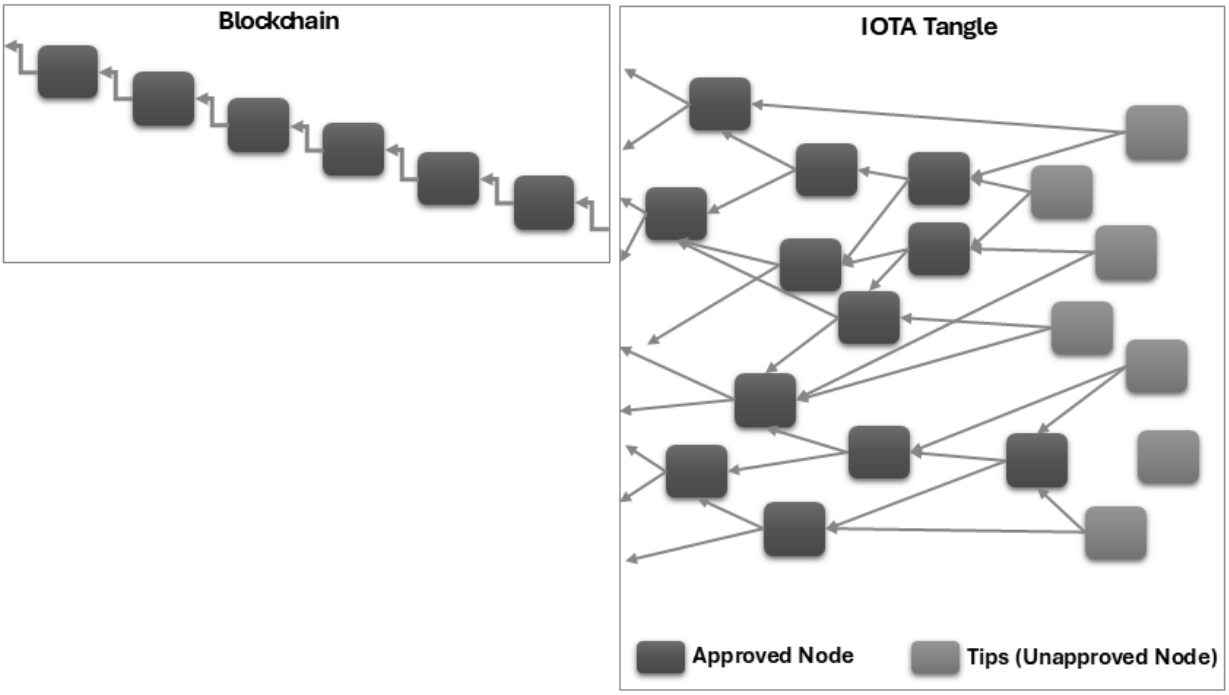

Figure 3. Comparison of the structure of a blockchain and the IOTA Tangle (DAG).

Table 2. Score for IOTA.

IOTA	Value/Description	Score
Access	Public	10
Layer for data storage	L1, possible on higher levels	10
Price of a single transaction, USD/tx	0	10
Transaction Speed, TPS	Up to 1000	10
Data storage capacity, Byte	8192	10
Existing data security and protection features	WOTS signatures DAG architecture MAM Coordicide Kerl (SHA-3) algorithm	10
Community	Reddit: 144 000 followers (top 2%) X: 270 000 followers	5
Implementation complexity	Libraries: JavaScript/Node.js, Python, Java, C	10
Total score:		75

SIGNUM

History and Creators: The Signum blockchain evolved from Burstcoin, the first blockhain to implement the Proof of Capacity (PoC) consensus. Burstcoin was initially launched in 2014. The original creator of Burstcoin is an anonymous individual whose identity remains undisclosed. Burstcoin was later renamed to Signum and is supported by a community of developers and enthusiasts, with development now overseen by the Signum Foundation, making it an open and collaborative project.

Purpose: Signum was developed to be a sustainable and environmentally friendly blockchain platform, Figure 4. Its primary purpose is to provide solutions for smart contracts, decentralized applications, and various financial transactions without the need for costly and energy-intensive mining.

Architecture: Signum uses PoC+ (Proof of Commitment Plus), an advanced algorithm that combines PoC with PoS. Blocks are added to the existing chain every 4 minutes. This algorithm ensures the security of the network through mining that utilizes the existing hard drive space of users, with additional staking included for enhanced security and sustainability.

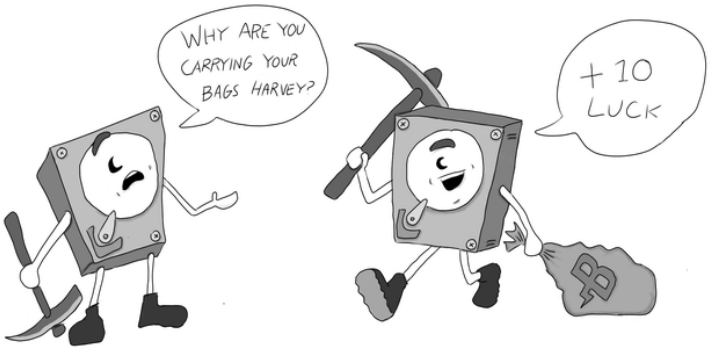

Figure 4. Harvey the hard drive – one of the mascots of Signum and PoC+ mining.

Consensus Algorithm: The PoC+ algorithm enables mining on the Signum network by utilizing the free space on a user's hard drive. Any user can "commit" disk space and participate in transaction validation. Transactions are added to blocks after being validated through the PoC+ algorithm, which is more energy-efficient compared to the PoW algorithm [34, 35]. This approach makes Signum a more sustainable and accessible blockchain solution, combining the benefits of both PoC and PoS, Table 3.

Table 3. Score for Signum.

Signum	Value/Description	Score
Access	Public	10
Layer for data storage	L1, possible on higher levels	10
Price of a single transaction, USD/tx	0,00001-0,00003	5
Transaction Speed, TPS	Up to 5 000	10
Data storage capacity, Byte	1000	5
Existing data security and protection features	Possible message encryption	10
Community	Reddit: 883 followers (top 21%) X: 2 580 followers	5
Implementation complexity	Signum Network SDK, JavaScript library	10
Total score:		65

ETHEREUM

History and Creators: Ethereum was first described in late 2013 in a white paper by Vitalik Buterin. Buterin was one of the co-founders of Bitcoin Magazine and a programmer at the time. Formal development of the Ethereum software began in 2014 through the Swiss company Ethereum Switzerland GmbH (EthSuisse). The public was first able to purchase Ethereum tokens (ether) during a public sale in July and August 2014. Ethereum was launched in 2015, with Buterin, along with Gavin Wood, Charles Hoskinson, and others, becoming one of the founders of Ethereum.

Purpose: Ethereum was designed as a decentralized platform that allows the creation of smart contracts and decentralized applications (dApps). Its purpose is to enable developers to create and deploy applications that operate without intermediaries, increasing efficiency and reducing transaction costs, Figure 5.

Architecture: Ethereum's unique architecture solution is based on a global virtual machine known as the Ethereum Virtual Machine (EVM). The EVM allows the execution of smart contracts in a decentralized manner, where each network participant holds a copy of the machine's state and can request the execution of any code. The architecture is designed so that all nodes on the network can agree on the current state and all executed transactions.

Consensus Algorithm: After using PoW initially, Ethereum transitioned to PoS in September 2022. In the PoS system, validators (who must stake a certain amount of ether as collateral) are randomly selected to propose blocks, which are then verified and added to the blockchain by other validators. This transition significantly reduced the energy consumption of the Ethereum network [36-38].

Additional Information: Transaction fees on Ethereum significantly fluctuate. Depending on the type of transaction, fees can be up to 100 times higher than those listed in Table 4. The fees in Table 4 refer to standard transactions between two Ethereum accounts. The website https://etherscan.io/gastracker provides real-time transaction fees on Ethereum.

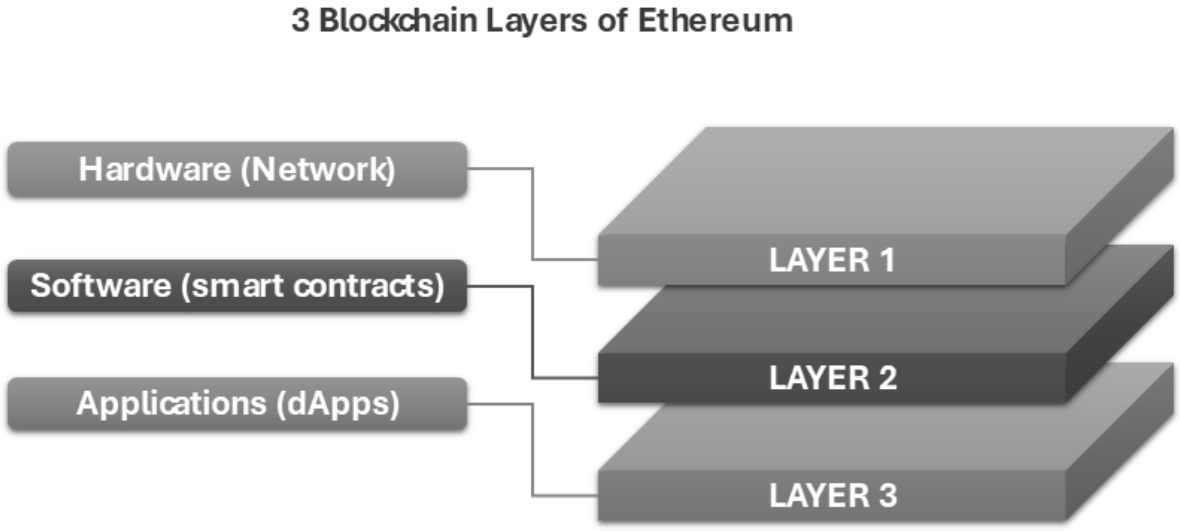

Figure 5. Ethereum layers.

Table 4. Score for Ethereum.

	Value/Description	Score
Access	Public	10
Layer for data storage	L1, possible on higher levels	10
Price of a single transaction [USD/tx]	0.06-0.09	0
Transaction Speed [TPS]	15-30 on L1 Up to 65 000 on L2	5
Data storage capacity [Byte]	Up to 220.588	5
Existing data security and protection features	Possible encryption, zK-SNARKs	10
Community	Reddit: 3 200 000 followers (top 1%) X: 3 400 000 followers	10
Implementation complexity	Libraries: Web3.js, Ether.js, Web3.py, Web3j, go-ethereum, ether-rs, web3swift	10
Total score:		65

The size of data that can be stored on Ethereum within a Layer 1 transaction is limited by the so-called "gas limit", which is 15 000 000. Theoretically, this allows for 220 588 bytes of data, but it is not possible to use the entire gas limit for data storage – some of the gas must be reserved for other operations necessary for executing the transaction. Additionally, using the

maximum gas for data storage would raise the cost of a single transaction to a level of complete unprofitability. Hence, the data storage capacity has been given a score of 5.

SOLANA

History and Creators: Solana was founded in 2017 by Anatoly Yakovenko. To overcome the limitations of scalability and transaction speed in existing blockchain networks, Yakovenko designed Proof of History (PoH) as a key innovation that enables faster and more scalable transactions, making Solana one of the fastest growing blockchain platforms.

Purpose: Solana is designed as a high-performance blockchain platform intended for decentralized applications (dApps) and financial systems, Figure 6. Its purpose is to provide infrastructure that can scale and support many users and transactions with minimal costs and delays, which is particularly beneficial for applications requiring fast transactions, such as gaming, payments, and NFTs.

Architecture: Solana utilizes a unique architecture that combines PoH with the Tower BFT consensus algorithm. PoH serves as a timestamp for all events on the network, allowing nodes to agree on the order of transactions without the need for direct communication. This enables the network to be extremely fast and efficient in processing transactions.

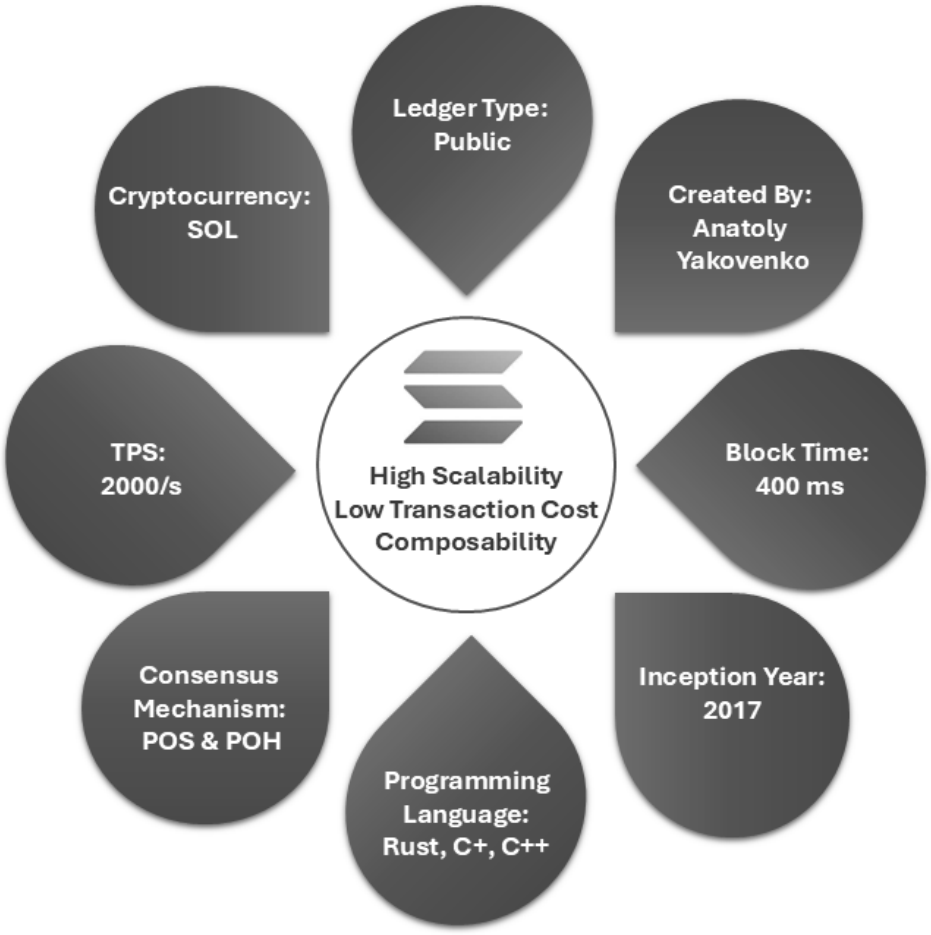

Figure 6. Solana features overview.

Consensus Algorithm: Solana employs a combination of PoS and PoH algorithms. PoH creates a cryptographic timestamp that allows transactions to be organized and processed more quickly, while PoS enables the validation of these transactions by validators who stake and lock their SOL tokens [39-41], Table 5.

Table 5. Score for Solana.

Solana	Value/Description	Score
Access	Public	10
Layer for data storage	L2, possible on higher levels	5
Price of a single transaction, USD/tx	0,00025	5
Transaction Speed, TPS	Up to 50 000	5
Data storage capacity, Byte	1 232, up to 10 MB per address	10
Existing data security and protection features	Possible encryption	10
Community	Reddit: 260 000 followers (top 1 %) X: 2 700 000 followers	10
Implementation complexity	Libraries: Solana Program Library (SPL), Anchor framework (all Rust)	5
Total score:		60

POLYGON

History and Creators: Polygon, formerly known as Matic Network, was launched in 2017 by four software engineers: Jaynti Kanani, Sandeep Nailwal, Anurag Arjun, and Mihailo Bjelic. The project was rebranded to Polygon Technology in 2021, Figure 7, with the aim of solving scalability and high transaction cost issues on the Ethereum network. Since then, Polygon has become one of the most popular Layer 2 solutions for Ethereum.

Purpose: Polygon was designed as a Layer 2 solution to enhance scalability and reduce transaction costs on the Ethereum network. Its primary purpose is to enable faster and cheaper transactions while maintaining the security and decentralization provided by Ethereum.

Architecture: Polygon uses a layered architecture with a PoS chain as its foundation, known as the Polygon PoS Chain. This architecture allows for fast transaction processing and supports various Layer 2 solutions such as Plasma and zk-rollups. The Polygon PoS chain connects with the Ethereum network via smart contracts, ensuring security and interoperability.

Consensus Algorithm: Polygon uses the PoS consensus algorithm, which requires validators to lock a certain amount of MATIC tokens as collateral to participate in transaction validation, for which they receive a commission. Validators are randomly selected based on their stake, and their reward is paid in MATIC tokens. This model significantly reduces energy consumption compared to the PoW algorithm [42, 43], Table 6.

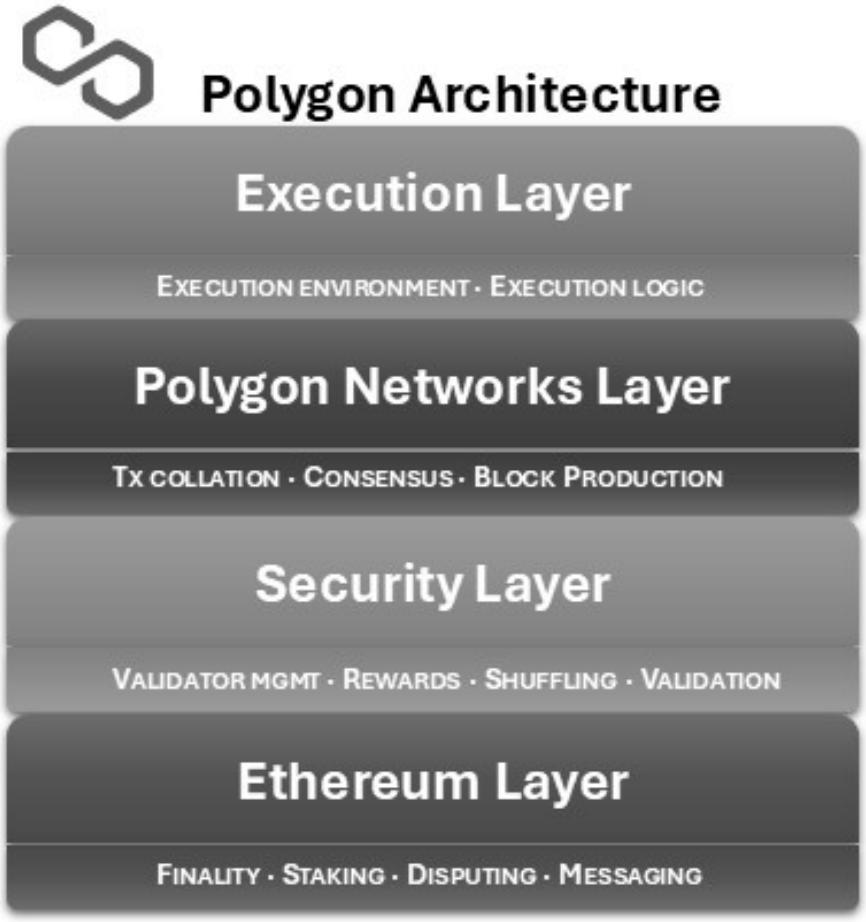

Figure 7. Polygon architecture overview.

Table 6. Score for Polygon.

Polygon	Value/Description	Score
Access	Public	10
Layer for data storage	L2, possible on higher levels	5
Price of a single transaction [USD/tx]	0,01	0
Transaction Speed [TPS]	Up to 65 000	5
Data storage capacity [Byte]	Up to several hundred Byte (more data requires paying additional fees)	5
Existing data security and protection features	Possible encryption, zk-SNARKs	10
Community	Reddit: 61 000 followers (top 2%) X: 2 000 000 followers	10
Implementation complexity	Libraries in Rust, CLI tools	10
Total score:		55

STELLAR

History and Creators: The Stellar blockchain was launched in 2014 by Jed McCaleb, who previously founded Mt. Gox and co-founded Ripple. McCaleb, together with Joyce Kim, launched Stellar as a fork of Ripple, with the goal of creating a network that enables fast and low-cost international transactions. Since then, Stellar has become recognized as a platform connecting financial institutions, payments, and users in a decentralized environment.

Purpose: Stellar was designed as a global marketplace to facilitate cheap and fast international transactions using various currencies. Its primary goal is to provide access to financial services, especially for people in underdeveloped regions, while reducing the cost of money transfers.

Architecture: Stellar operates a decentralized network that relies on a distributed ledger, Figure 8. This architecture allows all nodes in the network to synchronize information every

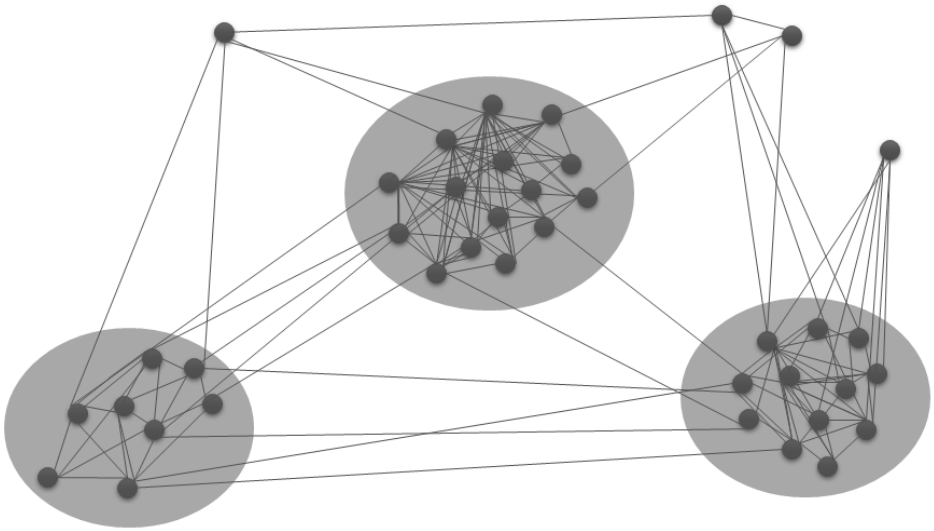

Figure 8. Simplified visualization of nodes and quorum slices on the Stellar network.

Table 7. Score for Stellar.

Stellar	Value/Description	Score
Access	Public	10
Layer for data storage	L2, possible on higher levels	5
Price of a single transaction, USD/tx	0,00025	5
Transaction Speed, TPS	Up to 50 000	5
Data storage capacity, Byte	28	5
Existing data security and protection features	Possible encryption	10
Community	Reddit: 259 000 followers (top 1%) X: 2 700 000 followers	10
Implementation complexity	Libraries: Wallet SDK, JS SDK, dev tools	10
Total score:		60

few seconds, enabling fast transactions, Table 7. The system is also open, allowing anyone to set up a Stellar node and participate in the network.

Consensus Algorithm: Stellar uses the Stellar Consensus Protocol, based on the Federated Byzantine Agreement model. This protocol enables rapid consensus between nodes through quorum slices, significantly speeding up transactions compared to traditional blockchain models [44-46].

HYPERLEDGER SAWTOOTH

History and Creators: Hyperledger Sawtooth is one of the projects under the Hyperledger umbrella, launched by the Linux Foundation in 2016. Sawtooth was primarily developed by Intel with the goal of providing a flexible and modular solution for building and deploying distributed applications. As part of the Hyperledger family, Sawtooth is open-source and designed for a wide range of industrial applications.

Purpose: Hyperledger Sawtooth is designed to enable easy programming and development of blockchain applications, focusing on security, scalability, and modularity. Its purpose is to provide infrastructure that supports various industrial uses, including financial services, IoT, and supply chain management, enabling customized blockchain networks that meet the specific needs of organizations.

Architecture: The modular Sawtooth architecture separates the core system from the application domain. The modularity allows defining and implementing business rules without having to understand the system's internal design. Sawtooth's architecture enables parallel transaction execution, increasing network efficiency and scalability, and can run as a permissioned or permissionless network, making it adaptable to various use scenarios.

Consensus Algorithm: Sawtooth supports multiple consensus algorithms, including Proof of Elapsed Time (PoET), Practical Byzantine Fault Tolerance, and Raft. PoET is particularly notable for using Intel SGX security features to generate random time intervals, allowing for energy-efficient consensus without requiring high computational resources [47-49], Table 8.

Table 8. Score for Hyperledger Sawtooth.

Hyperledger Sawtooth	Value/Description	Score
Access	Private	0
Layer for data storage	L1, possible on higher levels	10
Price of a single transaction [USD/tx]	0, configurable	10
Transaction Speed [TPS]	Depending on the configuration	5
Data storage capacity [Byte]	Depending on the configuration	5
Existing data security and protection features	Possible encryption, DDoS protection	10
Community	Reddit: 3 800 followers (top 11 %) X: 78 100 followers	5
Implementation complexity	Open-source code	10
Total score:		55

Additional Information: Hyperledger Sawtooth differs from other blockchain platforms considered in this article in that it does not have a public platform maintained by miners and validators with open access – hence, the access parameter is scored 0. Although the code is open-source and can be executed on personal infrastructure and configured according to specific needs, this significantly increases the costs of creating a solution for storing IoT data. While it's possible to configure blockchain parameters to make transactions free, one must use their own infrastructure and establish a network of validators and miners.

CONCLUSION

After applying the methodology described in previous chapters and scoring each of the selected blockchain solutions, we present consolidated scores in Table 9.

Table 9. Consolidated scores.

	IOTA	Signum	Ethereum	Solana	Polygon	Stellar	Hyper-ledger Sawtooth
Access	10	10	10	10	10	10	0
Layer for data storage	10	10	10	5	5	5	10
Transaction price, USD/tx	10	5	0	5	0	5	10
Transaction Speed, TPS	10	10	5	5	5	5	5
Data storage capacity, Byte	10	5	5	10	5	5	5
Existing data security and protection features	10	10	10	10	10	10	10
Community	5	5	10	10	10	10	5
Implementa-tion complexity	10	10	10	5	10	10	10
Total score:	**75**	**65**	**65**	**60**	**55**	**60**	**55**

Among the selected blockchain platforms, IOTA achieved the highest overall score, totaling 75 out of 80. IOTA received top scores in every parameter except "Community," supporting data storage of over 8 kB per transaction on Layer 1. The platform enables feeless transactions and can reach up to 1000 transactions per second on Layer 1. Developed by the IOTA Foundation, the platform benefits from a strong foundation of libraries and documentation, which offsets its relatively small social media community. These attributes make IOTA the most suitable platform among the seven evaluated for storing IoT data.

Ethereum scored 65 out of 80, bolstered by its popularity and a large, active community. However, its suitability for IoT data storage is hindered by volatile transaction fees, lower transaction speeds on Layer 1, and limited clarity regarding data storage capacity per transaction. Signum also achieved a score of 65, offering Layer 1 messaging capabilities and allowing up to 1000 bytes of encrypted data per transaction. While promising, its limitations include transaction costs and a relatively small community supporting the network.

Solana, Polygon, and Stellar provide data storage capabilities on Layer 2, which introduces additional costs and complexities for implementing IoT data storage solutions. Hyperledger Sawtooth, along with Polygon, scored 55 out of 80. Unlike the other platforms, Hyperledger Sawtooth does not have a public network available for general use. Its comparatively lower score reflects the configurable nature of transaction speed and data storage capacity, as we made no specific assumptions about the configuration of private instances.

FURTHER RESEARCH

Future research on blockchain's suitability for storing IoT data can be advanced in several directions:

- Expanding platform analysis – more blockchain platforms can be assessed using the methodology presented in this article to enhance the comparative insights provided by the scoring system,
- Methodology refinement – additional parameters and weighted scoring could be introduced to emphasize features most critical for IoT data storage, such as Layer 1 transaction speed versus community size,
- Practical validation – building a prototype IoT device that generates sensory data, coupled with a middleware to interface selected blockchain platforms, would enable real-world testing of relevant metrics like latency, storage capacity, efficiency, and cost. Such data can validate and refine the proposed methodology and offer practical benchmarks for future implementations.

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DEVELOPMENT OF LIFELONG LEARNING IN THE COUNTRIES OF THE EUROPEAN UNION: K-MEANS CLUSTER ANALYSIS EVALUATION

Ivana Vrdoljak*

University of Applied Health Sciences
Zagreb, Croatia

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ABSTRACT

The article analyses lifelong learning development across EU countries, focusing on disparities in doctoral education. A cluster analysis methodology is used to identify homogeneous groups of countries based on various indicators, such as the number of doctoral graduates divided by age and gender and GDP per capita. The analysis categorises countries into clusters based on similarities, applying the K-means clustering technique. This method groups countries to highlight differences in lifelong learning, particularly emphasising economic development. Cluster analysis reveals significant differences between economically advanced European countries and less developed regions, particularly in Eastern Europe. The results underline that Western European countries show a higher number of doctoral graduates, both in total and within the 25-34 age group, compared to Eastern European nations, where these figures are considerably lower. The study concludes that fostering lifelong learning is crucial for socio-economic development, and countries must implement strategies to enhance participation in higher education.

KEY WORDS

lifelong learning, cluster analysis, doctoral education, European Union, k-means clustering

CLASSIFICATION

JEL: C38, I23, O15

*Corresponding author, η: ivana.vrdoljak@zvu.hr; +385 1 5495 805;
Zdravstveno veleučilište, Mlinarska cesta 38, HR – 10 000 Zagreb, Croatia

INTRODUCTION

Lifelong learning has become a central component of modern education systems and a key factor in economic development, especially within the European Union (EU). As labour markets and technological advancements evolve rapidly, the ability of individuals to continuously update their skills and knowledge is crucial for maintaining employability, fostering personal development, and promoting social inclusion. European countries have made significant efforts to promote adult education, but participation levels and outcomes remain heterogeneous across the region [1]. The strategic framework for European cooperation in education and training, particularly through initiatives like the Europe 2020 strategy, underscores the importance of enhancing lifelong learning toss achieve sustainable economic growth and social cohesion [2].

This article aims to explore the development and participation in lifelong learning across selected EU member states and associated countries. The study focuses on key indicators of formal and non-formal education, trends in doctoral education, and the relationship between educational attainment and economic performance. Specifically, the paper investigates how different countries cluster based on their educational outcomes, using advanced statistical methods like cluster analysis, and assesses the socio-economic factors that influence participation rates in lifelong learning and higher education.

Through the use of Eurostat data from 2013 to 2019, this study presents a comparative analysis of lifelong learning indicators, PhD graduation rates, and GDP per capita across 35 European countries. The findings will shed light on the disparities between countries in terms of educational achievements, highlight the economic implications of lifelong learning, and suggest policy recommendations to enhance participation in adult education. By understanding the factors that contribute to successful lifelong learning frameworks, this paper aims to provide insights that can inform policymakers and educators in their efforts to improve educational systems across Europe.

LITERATURE REVIEW

The strategic framework for European cooperation in education and training, approved in May 2009, included a number of requirements for adult participation in learning, including the need for at least 15 % of people aged 25-64 to participate in lifelong learning [3]. In 2020, 9,2 % of EU citizens aged 25-64 were enrolled in some form of education or training, which is 0,9 percentage points less than in 2015 and 1,6 percentage points less than in 2015. Part of the decline in 2019 can be linked to the COVID-19 pandemic, which is why training programs have been suspended [4].

The adult learning indicator in the Labour Force Survey refers to participation in formal and non-formal education and training [5].

Results presented in [3] indicate that Denmark, Finland, and Sweden were the only EU member states that reported a significantly higher percentage of their adult population engaged in lifelong learning in the four weeks prior to the survey, ranging from 20.0 to 28.6%. Estonia, the Netherlands, and Luxembourg were the only other EU countries to have a participation percentage of over 15 % in 2020. Adult learning rates were less than 4% in Romania, Bulgaria, Slovakia, Croatia, and Poland, on the other hand. The reference period for participation is four weeks before the interview.

In addition, as reported in [3], women (10,0 % in 2020) are more likely than men (8,3 %) to participate in adult learning in the EU. Both men and women had lower participation rates in 2020 than five years earlier. Participation rates for women and men gradually increased until 2019 but decreased in 2020, coinciding with the onset of the COVID-19 outbreak. In all EU

Member States in 2020, women had higher participation rates than men, except for the Czech Republic, Germany, Greece and Cyprus (where men had higher rates), while Romania had the same rate for both sexes.

The Adult Education Survey, together with the data from the Labour Force Survey, which provides data on participation in education and training in the four weeks preceding the survey interview, also includes data on education and training [6]. Because the survey assesses engagement in learning activities over a longer period (12 months before the survey interview), it is more likely to cover more learning activities, resulting in higher rates of involvement in formal and non-formal education and training. However, this is not done as often as it should (every six years since 2016). The last wave of the survey was carried out in 2022, and before that in 2016.

In the 12 months preceding the EU-wide Labour Force Survey [6], men and women had almost similar rates of participation in education and training. In Cyprus, the Czech Republic, Hungary and Italy, men were much more likely than women to participate in education and training. In contrast, the opposite is true in Estonia, Finland, Latvia, Sweden and Lithuania. Younger individuals (aged 25-34) had more than 20 percentage points higher than those who said they would participate in the EU in 2016. The participation of older people in education and training was extremely low in Romania and Greece. Educational achievement is linked to the likelihood of inclusion in education and training: those with higher education reported the highest participation rates, while those with lower secondary education reported the lowest participation rates.

In the reference period of 2022, 55 % of persons aged 25-64 reported engaging in lifelong learning (formal and/or non-formal education), an increase from 54 % in 2017. In 2022, little more than 11 % of persons aged 25-64 engaged in formal education, reflecting a 2 % rise from 2017. In 2022, 50 % of persons aged 25-64 engaged in non-formal education, maintaining the same participation percentage as in 2017. In 2022, over half (54 %) of adults aged 25-64 reported participating in informal learning, a decrease from 62 % in 2017 [7].

It is also common knowledge that the European Commission has emphasised for many years the importance of lifelong learning in achieving Lisbon's goals, especially in terms of personal growth and fulfilment. As a result, since 2005, a public debate on the future of social policy has developed in the European Union. In this context, lifelong learning plays a key role in building a common European socio-economic paradigm [8].

EU-SILC statistics show a high level of reliability in the literature on adult education and training [9]. The formal phenomenon of lifelong learning is significantly higher among younger and more educated employees and significantly lower among workers who have changed jobs in the last year and work in small enterprises or low-skilled occupations, statistics show for both men and women. According to estimates for both genders in the full sample, employees are far more likely to engage in formal lifelong learning for a fixed and fixed-term period. These two explanatory factors also had the greatest impact on the likelihood of adult subsequent learning. In fact, lifelong learning remains a key goal for European countries, as people need to update their skills throughout their working lives to improve employment prospects and contribute to personal fulfilment, social inclusion, and active citizenship in an era of rapidly changing technologies. Many countries are changing their institutional frameworks to ensure that everyone has access to high-quality lifelong learning opportunities (European Commission, 2010). However, empirical research on the factors of lifelong learning in European countries is insufficient [9].

METHODOLOGY

The research presented in the paper consists of two parts. First, the trends in the number of completed PhDs in selected European countries are explored. Data on the number of completed PhDs per 1000 inhabitants and the number of men and women who received PhDs per 1000

inhabitants are analysed, with special emphasis on the age group from 25 to 34. Data was collected from the Eurostat database. Second, the homogeneity of lifelong learning in selected European countries is analysed.

Cluster analysis is a useful approach for detecting homogeneous groups of units, objects, instances, or observations. As a result, units in the same cluster share many similarities. Units belonging to different clusters, on the other hand, have a wide range of features. The choice of the most acceptable variables for grouping must be determined at the initial stage of the cluster analysis. The variables used are determined by the theory used and the preferences of the researchers. However, the ratio of the number of variables to the sample size should be considered when selecting variables.

The grouping technique determines how clusters are generated. Clustering strategies vary depending on the optimisation goal, such as minimising variation between units in clusters or increasing the distance between units in different clusters [10]. Other techniques for grouping procedures exist, but they can be categorised into hierarchical and non-hierarchical methods [11].

Different distance measurements are used to generate clusters of units in hierarchical cluster analysis [12]. Clusters are generated by using variations within clusters in non-hierarchical cluster analysis. Additionally, in hierarchical cluster analysis, the total number of clusters is determined after the study is completed. However, in non-hierarchical cluster analysis, the final number of clusters is determined before the cluster analysis begins [12]. Units in hierarchical cluster analysis do not change their cluster affiliation, but this is a possibility in non-hierarchical cluster analysis. The stability and validity of the cluster solution are tested at the end [13]. If multiple clustering algorithms produce comparable results, the cluster solution can be considered stable. A cluster analysis was carried out with regard to the above factors.

The first phase involves undertaking a descriptive statistical study on the characteristics of 35 European countries. This study aims to understand better the differences between the countries studied. The analysis of descriptive statistics also serves as a foundation for cluster analysis.

The number of alternate partitions of n units in a k cluster is described by [14] as:

$$N(n,k) = \frac{1}{k!}\sum_{m=1}^{k}(-1)^{k-m}\binom{k}{m}m^n \tag{1}$$

where n is the number of units, k is the number of clusters. The problem is that even with a small n and k, the number of alternate partitions is still large. There are 35 European countries in the analysis, which implies that there are many different divisions. As a result, a non-hierarchical (partition) clustering technique was chosen to perform cluster analysis. The k-means approach is also used here because it is efficient in computer science and the most popular among scientists [15]. As its name implies, the k-mean grouping process deals with observing the means of clusters. An iterative process of simultaneously moving units to the cluster with the nearest mean is included in the k-mean grouping algorithm. A new cluster mean is then determined [13]. Obviously, there are several stages in the technique of grouping k-mean values.

In the first stage, the initial solution is determined by taking into account the specified number of clusters and starting centres or by observing the p-dimensional vector for each set:

$$x^{\sim \mathrm{m}} = \left(x_1^{\sim \mathrm{m}}, x_2^{\sim \mathrm{m}}, ..., x_p^{\sim \mathrm{m}}\right) \tag{2}$$

where $x_k^{\sim m}$ describes the k-th characteristic of the initial seed of cluster m [13]. Euclidean square distances can be used to calculate the distance between the ith unit and the initial seed of the cluster m as stated:

$$d_{ix^{\sim \mathrm{m}}}^2 = \sum_{k=1}^{p}\left(x_{ik} - x_k^{\sim \mathrm{m}}\right)^2 \tag{3}$$

These distances are calculated for all clusters, and the ith unit is assigned to the cluster with the shortest distance. This allows all units to be assigned to specific clusters. The cluster mean is performed in the next step by flashing all units associated with a particular cluster. To achieve this, each of the dimensions of the p attribute is examined:

$$\bar{x}^m = \left(\bar{x}_1^m, \bar{x}_2^m, ..., \bar{x}_p^m\right) \quad (4)$$

Subsequently, the cluster mean $\bar{x}^m$ replaces the initial seeds $x^{\sim m}$, and the distances between each unit and each cluster centre are recalculated using equation 3 [13].

As a result, units can "travel" from one cluster to another. This process continues until no units change their membership in the cluster. The cluster solution is then declared stable, and a final solution is reached. The contents of the cluster are then discussed and understood in the next stage.

This research uses the statistical program Statistica (version 13.1) to perform cluster analysis. The final cluster solution is performed by observing the average values of the six variables used in cluster analysis for units within the cluster. This explains the main properties of the units in clusters.

The v-fold cross-check strategy was chosen to identify a finite number of clusters in order to select the optimal number of clusters [16]. The data is initially split into v strata or subsamples of approximately similar size in a v-fold cross-validation procedure. In the following stages, each subsample is removed, and the remaining subsamples are used to estimate the value of the removed subsample. The estimated errors for all summed subsamples are compared with the errors from previous iterations. Finally, [17] select the solution with the lowest projected error rate. It has been shown that, in most cases, it is sufficient to extract 10 (v = 10) random subsamples from the data [16]. As a result, it was placed at the same number in our analysis.

Further restriction is imposed in order to obtain meaningful and interpretive clusters. As a result, the final cluster count should be somewhere between 2 and 25. If the relevant error function for a solution with a k + 1 cluster is not at least 5 % better than the solution with a k cluster, the solution with a k cluster is considered final [18].

Cluster analysis has emerged as a valuable tool in educational research, enabling the identification of distinct student profiles based on various learning behaviours and motivational factors. For example, cluster analysis has been used to explore how physical education students regulate their motivation, identifying unique combinations of intrinsic and extrinsic motivations that influence performance and engagement [19]. The method has been applied to categorise student behaviours in educational settings, highlighting how unsupervised techniques can reveal patterns in student engagement and academic performance [20]. Similarly, cluster analysis has been proven useful in examining the impact of external factors, such as the COVID-19 pandemic, on e-learning, identifying variations in response across different countries based on development levels [21]. Further research used cluster analysis to investigate employment trends in knowledge-intensive fields, emphasising gender disparities in European countries [22].

RESULTS

TREND OF LIFELONG LEARNING DEVELOPMENT IN SELECTED EUROPEAN COUNTRIES

Total number of completed PhDs per 1000 inhabitants

Table 1 shows the total number of completed PhDs per 1000 inhabitants. From 2013 to 2019, statistics for 35 European countries (EU member states plus Iceland, Norway, Montenegro, Macedonia, Serbia and Turkey) were collected from the European Commission's statistical database – Eurostat. The highest number of PhD graduates per 1000 inhabitants in 2019 was

Table 1. Completed PhDs, number per 1000 inhabitants (n.d. – no data).

Country / Year	2013	2014	2015	2016	2017	2018	2019
EU – 27 countries (as of 2020)	1.8	1.8	1.9	1.9	1.9	1.9	1.7
EU – 28 countries (2013-2020)	1.9	1.9	2.0	2.1	2.1	2.1	1.9
Belgium	1.7	1.8	1.9	2.0	2.0	2.1	2.0
Bulgaria	1.2	1.4	1.5	1.5	1.5	1.5	1.4
Czech Republic	1.6	1.7	1.7	1.7	1.7	1.7	1.7
Danish	2.9	3.2	3.3	3.2	3.2	2.9	2.8
Germany	2.7	2.8	2.9	2.8	2.7	2.6	2.7
Estonia	1.2	1.1	1.1	1.2	1.3	1.3	1.3
Ireland	2.1	2.5	2.1	2.4	2.2	2.3	2.5
Greece	1.0	1.1	1.3	1.5	1.5	1.3	1.5
Spain	1.6	1.8	1.9	2.6	3.7	3.2	1.8
France	1.7	1.7	1.8	1.7	1.7	1.7	1.7
Croatia	1.4	1.5	1.6	1.2	1.3	1.3	1.4
Italy	1.5	1.5	1.5	1.4	1.4	1.2	1.2
Cyprus	0.4	0.4	0.6	0.7	0.7	0.8	0.9
Latvia	1.1	0.9	0.9	0.7	0.5	0.5	0.5
Lithuania	1.2	1.1	1.1	0.9	0.9	0.9	0.9
Luxembourg	0.8	1.0	1.3	1.2	1.7	1.5	1.1
Hungary	0.8	0.9	1.0	1.0	1.0	1.0	1.0
Malta	0.4	0.3	0.5	0.5	0.7	0.7	0.5
Netherlands	2.1	2.2	2.3	2.4	2.2	2.2	n.d.
Austria	2.0	2.0	1.9	1.9	2.2	2.3	1.8
Poland	0.6	0.6	0.6	0.6	0.5	0.6	0.7
Portugal	1.9	2.0	1.9	2.0	1.8	2.0	1.9
Romania	1.9	1.4	1.5	0.8	0.7	0.7	0.8
Slovenia	4.0	3.5	3.5	3.8	1.9	1.8	1.9
Slovakia	2.4	2.5	2.2	2.1	2.0	1.7	1.8
Finnish	2.8	2.9	2.9	2.9	2.6	2.6	2.5
Sweden	2.8	2.9	2.9	2.7	2.7	2.3	2.3
Island	1.2	1.9	1.4	1.5	1.3	1.2	1.7
Liechtenstein	2.6	3.7	2.8	5.7	5.6	3.5	5.7
Norway	2.3	2.1	2.0	1.9	2.1	2.1	2.2
Switzerland	3.3	3.5	3.4	3.4	3.6	3.6	3.7
United Kingdom	3.0	2.9	3.0	3.1	3.1	3.3	3.3
North Macedonia	0.7	0.6	0.8	0.6	0.6	0.8	0.6
Serbia	n.d.	0.8	1.1	1.1	1.7	1.0	0.9
Turkey	n.d.	0.4	0.4	0.5	0.5	0.6	0.6

observed in economically advanced Western European countries, with Liechtenstein leading at 5,7, followed by Switzerland (3,7), the United Kingdom (3,3), Denmark (2,8), Germany (2,7), Ireland (2,5), and Finland (2,5). These figures remained stable between 2013 and 2019. In contrast, countries such as Cyprus (0.9), Latvia (0,5), Poland (0,5), and Turkey (0,6) recorded significantly lower rates, lagging the EU average of 1,9 PhDs per 1000 inhabitants during the same period. The data suggests that PhD attainment is more concentrated in economically and socially developed nations, with expectations of growth in developing countries as their education systems improve.

Total number of completed PhDs per 1000 population aged 25 to 34

To extend the analysis, Table 2 shows the total number of PhD graduates aged 25 to 34 per 1000 population for the period from 2013 to 2019. Data are not available for the European Union average in 2013 and 2014, the Netherlands in 2019, Romania for the period 2014-2017, and Serbia and Turkey for 2013. It can be noted that Germany (2,1 per 1000 inhabitants aged 25 to 34), Liechtenstein (2,1 per 1000 inhabitants aged 25 to 34), Switzerland (2,9 per 1000 inhabitants aged 25 to 34) and the United Kingdom (2,0 per 1000 inhabitants aged 25 to 34) achieved a significantly higher number of PhDs in 2019 compared to other countries and the European Union average for the period 2013 to 2019 which was 1,4 per 1000 residents from 25 to 34 years old. Indeed, doctoral studies are vital for determining the future career of scientists in the labour market, and Eastern European researchers are in a somewhat worse situation than their counterparts from Western Europe and the Nordic countries.

Table 2. Completed PhDs aged 25-34, number per 1000 population (n.d. – no data)**.** Source: Eurostat.

Country / Year	2013	2014	2015	2016	2017	2018	2019
EU – 27 countries (as of 2020)	n.d.	n.d.	1.3	1.3	1.3	1.3	1.2
EU – 28 countries (2013-2020)	1.4	1.3	1.4	1.4	1.4	1.4	1.4
Belgium	1.3	1.4	1.4	1.5	1.5	1.6	1.6
Bulgaria	0.4	0.5	0.5	0.6	0.6	0.6	0.5
Czech Republic	1.1	1.2	1.2	1.1	1.2	1.2	1.1
Danish	2.0	2.3	2.3	2.2	2.2	2.0	2.0
Germany	2.2	2.3	2.3	2.2	2.1	2.1	2.1
Estonia	0.8	0.7	0.6	0.8	0.8	0.8	0.8
Ireland	1.5	1.8	1.4	1.6	1.4	1.4	1.5
Greece	0.5	0.4	0.5	0.7	0.6	0.5	0.6
Spain	0.9	1.0	1.1	1.2	1.2	1.5	1.1
France	1.2	1.2	1.2	1.2	1.4	1.4	1.4
Croatia	0.8	0.8	0.8	0.5	0.6	0.5	0.5
Italy	1.2	1.1	1.2	1.1	1.1	1.0	1.0
Cyprus	0.3	0.3	0.3	0.5	0.4	0.6	0.6
Latvia	0.5	0.5	0.5	0.4	0.2	0.2	0.3
Lithuania	0.8	0.8	0.8	0.6	0.7	0.7	0.6
Luxembourg	0.7	0.8	1.1	1.0	1.3	1.2	1.1
Hungary	0.5	0.6	0.6	0.6	0.6	0.7	0.6
Malta	0.2	0.2	0.2	0.2	0.4	0.3	0.2
Netherlands	1.8	1.9	1.9	2.0	1.9	1.8	n.d.
Austria	1.5	1.5	1.4	1.4	1.4	1.3	1.3
Poland	0.5	0.4	0.5	0.5	0.4	0.5	0.5
Portugal	0.8	0.8	0.7	0.8	0.8	0.8	0.8
Romania	1.1	n.d.	n.d.	n.d.	n.d.	0.4	0.4
Slovenia	2.7	2.0	2.0	4.0	1.2	1.1	1.0
Slovakia	1.8	1.8	1.7	1.6	1.5	1.3	1.3
Finnish	1.2	1.3	1.3	1.3	1.1	1.2	1.1
Sweden	1.6	1.7	1.7	1.6	1.5	1.3	1.3
Island	0.6	0.9	0.6	0.8	0.6	0.5	0.9
Liechtenstein	1.5	1.5	1.5	2.6	2.6	1.5	2.1
Norway	1.2	1.1	0.9	1.0	1.0	1.0	1.1
Switzerland	2.6	2.7	2.6	2.7	2.8	2.8	2.9
United Kingdom	1.9	1.8	1.9	1.9	2.0	2.0	2.0
North Macedonia	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Serbia	n.d.	0.3	0.4	0.5	0.5	0.5	0.4
Turkey	n.d.	0.2	0.3	0.3	0.3	0.3	0.3

Total number of male PhDs per 1000 inhabitants

Table 3 shows the number of male graduates per 1000 inhabitants. As for the number of male graduates per 1000 inhabitants in the period from 2013 to 2019, it can be noted that Cyprus is recording an increasing trend in the number of male PhDs, in contrast to Italy, Latvia, Lithuania, Slovenia, Slovakia, Romania which has been recording a decline over the years. The average of the 28 countries in the European Union for the period 2013-2020 seems to maintain a stable trend in terms of male graduates at doctoral level over the years (≈ 1,1 men per 1000 inhabitants). The highest number of PhD graduates was recorded in Belgium (1,2 men per 1000 population), Denmark (1,4 men per 1000 population), Germany (1,5 men per 1000 population),

Table 3. Completed PhDs**,** number of men per 1000 inhabitants (n.d. – no data). Source: Eurostat.

Country / Year	2013	2014	2015	2016	2017	2018	2019
EU – 27 countries (as of 2020)	0.9	0.9	1.0	1.0	1.0	1.0	0.9
EU – 28 countries (2013-2020)	1.0	1.0	1.1	1.1	1.1	1.1	1.0
Belgium	1.0	1.0	1.1	1.1	1.1	1.2	1.2
Bulgaria	0.6	0.7	0.7	0.7	0.7	0.7	0.6
Czech Republic	0.9	1.0	0.9	1.0	1.0	1.0	1.0
Danish	1.6	1.7	1.7	1.7	1.6	1.5	1.4
Germany	1.5	1.5	1.6	1.5	1.5	1.4	1.5
Estonia	0.5	0.5	0.5	0.6	0.6	0.7	0.6
Ireland	1.1	1.3	1.1	1.2	1.1	1.1	1.2
Greece	0.6	0.6	0.7	0.8	0.8	0.7	0.8
Spain	0.8	0.9	1.0	1.3	1.8	1.5	0.9
France	1.0	0.9	1.1	1.0	0.9	1.0	1.0
Croatia	0.7	0.7	0.7	0.5	0.6	0.6	0.6
Italy	0.7	0.7	0.7	0.7	0.7	0.6	0.6
Cyprus	0.2	0.2	0.3	0.3	0.3	0.4	0.4
Latvia	0.5	0.4	0.4	0.3	0.2	0.2	0.2
Lithuania	0.5	0.5	0.5	0.4	0.4	0.4	0.4
Luxembourg	0.5	0.6	0.7	0.7	0.9	1.0	0.7
Hungary	0.4	0.5	0.5	0.5	0.5	0.6	0.5
Malta	0.2	0.3	0.2	0.3	0.4	0.3	0.3
Netherlands	1.1	1.2	1.2	1.2	1.2	1.1	n.d.
Austria	1.1	1.1	1.1	1.1	1.2	1.3	1.1
Poland	0.3	0.3	0.3	0.3	0.2	0.3	0.3
Portugal	0.8	0.9	0.9	0.9	0.8	0.9	0.9
Romania	0.9	0.7	0.7	0.4	0.3	0.3	0.4
Slovenia	1.8	1.5	1.5	5.3	1.0	0.8	0.9
Slovakia	1.2	1.3	1.1	1.0	1.0	0.9	0.9
Finnish	1.4	1.4	1.4	1.4	1.2	1.3	1.2
Sweden	1.5	1.6	1.6	1.5	1.5	1.2	1.3
Island	0.6	0.8	0.7	0.5	0.4	0.5	0.8
Liechtenstein	1.1	2.8	1.5	3.5	3.5	1.9	4.2
Norway	1.2	1.1	1.0	1.0	1.0	1.0	1.1
Switzerland	1.9	2.0	1.9	1.9	2.0	2.0	2.0
United Kingdom	1.6	1.5	1.6	1.7	1.7	1.7	1.7
North Macedonia	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Serbia	n.d.	0.4	0.5	0.5	0.7	0.4	0.5
Turkey	n.d.	0.2	0.2	0.3	0.2	0.3	0.3

Ireland (1,2 men per 1000 population), Austria (1,1 men per 1000 population), Finland (1,2 men per 1000 population), Sweden (1,3 men per 1000 population), Norway (1,1 men per 1000 population), Switzerland (2,0 men per 1000 inhabitants), the United Kingdom (1,7 men per 1000 inhabitants) with a significantly higher number in Liechtenstein (4,2 men per 1000 inhabitants). The data show that there is a significantly lower number of male graduates in doctoral studies in Cyprus (0,4 men per 1000 population), Latvia (0,2 men per 1000 population), Lithuania (0,4 men per 1000 population), Malta (0,3 men per 1000 population), Poland (0,3 men per 1000 population), Romania (0,4 men per 1000 population), North Macedonia (0,3 men per 1000 population), Serbia (0,5 men per 1000 inhabitants) and Turkey (0,3 men per 1000 inhabitants).

Total number of completed male PhDs per 1000 inhabitants aged 25 to 34

Furthermore, Table 4 presents data on the total number of male doctoral students aged 25 to 34 per 1000 population. It can be noted that the average of the European Union for the 28 countries for the period 2013 and 2020 is stable, as well as in the Netherlands, Poland, and North Macedonia. In addition, an increasing trend in the number of PhD holders over the years can be observed in Belgium, France, and Switzerland, while the opposite is true for Lithuania and Sweden.

Table 4. Completed male PhDs**,** age 25-34 per 1000 inhabitants (n.d. – no data). Source: Eurostat (continued on p.772).

Country / Year	2013	2014	2015	2016	2017	2018	2019
EU – 27 countries (as of 2020)	n.d.	n.d.	0.7	0.7	0.7	0.7	0.7
EU – 28 countries (2013-2020)	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Belgium	0.7	0.7	0.8	0.8	0.8	0.9	0.9
Bulgaria	0.2	0.2	0.3	0.3	0.3	0.2	0.2
Czech Republic	0.6	0.7	0.7	0.6	0.7	0.7	0.6
Danish	1.2	1.3	1.3	1.3	1.2	1.1	1.1
Germany	1.2	1.2	1.2	1.2	1.1	1.1	1.1
Estonia	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Ireland	0.8	0.9	0.7	0.8	0.7	0.7	0.8
Greece	0.3	0.2	0.3	0.3	0.3	0.3	0.3
Spain	0.4	0.4	0.5	0.5	0.5	0.7	0.5
France	0.7	0.7	0.7	0.7	0.8	0.8	0.8
Croatia	0.3	0.4	0.3	0.2	0.3	0.2	0.3
Italy	0.6	0.5	0.6	0.5	0.6	0.5	0.5
Cyprus	0.1	0.1	0.1	0.2	0.2	0.3	0.2
Latvia	0.3	0.2	0.2	0.2	0.1	0.1	0.1
Lithuania	0.4	0.4	0.4	0.3	0.3	0.3	0.3
Luxembourg	0.4	0.5	0.6	0.6	0.7	0.7	0.6
Hungary	0.3	0.3	0.3	0.3	0.3	0.4	0.3
Malta	0.1	0.2	0.1	0.1	0.2	0.2	0.1
Netherlands	1.0	1.0	1.0	1.0	1.0	1.0	n.d.
Austria	0.8	0.9	0.8	0.8	0.8	0.8	0.8
Poland	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Portugal	0.4	0.4	0.3	0.3	0.3	0.4	0.4
Romania	0.5	n.d.	n.d.	n.d.	n.d.	0.2	0.2
Slovenia	1.3	0.9	0.9	1.6	0.7	0.5	0.5
Slovakia	0.8	0.9	0.8	0.7	0.7	0.6	0.6
Finnish	0.7	0.7	0.7	0.7	0.6	0.7	0.6
Sweden	1.0	1.0	1.0	1.0	0.9	0.8	0.8

Table 4. Completed male PhDs**,** age 25-34 per 1000 inhabitants (n.d. – no data). Source: Eurostat (continuation from p.771).

Country / Year	2013	2014	2015	2016	2017	2018	2019
Island	0.3	0.4	0.4	0.3	0.2	0.2	0.5
Liechtenstein	0.4	0.9	0.9	1.3	1.3	0.6	1.5
Norway	0.7	0.6	0.5	0.5	0.6	0.6	0.6
Switzerland	1.4	1.5	1.5	1.5	1.5	1.6	1.6
United Kingdom	1.0	1.0	1.0	1.1	1.1	1.1	1.1
North Macedonia	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Serbia	n.d.	0.1	0.2	0.2	0.2	0.2	0.2
Turkey	n.d.	0.1	0.1	0.1	0.1	0.2	0.1

Total number of completed female PhDs per 1000 population

Table 5 represents the total number of female PhD graduates aged 25 to 34 per 1000 population. It is worth noting that the European Union average for the 27 countries as of 2020 has been quite stable over time. In addition, the number of individuals with PhDs increased over the years in Belgium, France, and Switzerland). A positive trend in the analysed period can be observed in Belgium, Bulgaria, Poland, Switzerland, and Turkey, while Italy, Lithuania, and Romania recorded the opposite trend.

Table 5. Completed PhDs**,** number of women per 1000 inhabitants (n.d. – no data). Source: Eurostat (continued on p.773).

Country / Year	2013	2014	2015	2016	2017	2018	2019
EU - 27 countries (as of 2020)	0.9	0.9	0.9	0.9	0.9	0.9	0.8
EU - 28 countries (2013-2020)	0.9	0.9	1.0	1.0	1.0	1.0	0.9
Belgium	0.7	0.8	0.8	0.9	0.9	0.9	0.9
Bulgaria	0.6	0.7	0.7	0.8	0.8	0.8	0.8
Czech Republic	0.7	0.7	0.7	0.7	0.7	0.8	0.7
Danish	1.3	1.5	1.6	1.6	1.5	1.4	1.4
Germany	1.2	1.3	1.3	1.3	1.2	1.2	1.2
Estonia	0.7	0.6	0.6	0.7	0.8	0.6	0.7
Ireland	1.0	1.2	1.0	1.2	1.1	1.2	1.3
Greece	0.5	0.6	0.6	0.8	0.7	0.6	0.7
Spain	0.8	0.9	1.0	1.3	1.8	1.7	0.9
France	0.8	0.7	0.7	0.7	0.8	0.8	0.8
Croatia	0.8	0.8	0.9	0.6	0.7	0.7	0.8
Italy	0.8	0.8	0.8	0.7	0.7	0.6	0.6
Cyprus	0.2	0.2	0.3	0.4	0.3	0.4	0.5
Latvia	0.6	0.6	0.5	0.4	0.3	0.2	0.3
Lithuania	0.7	0.7	0.7	0.5	0.5	0.5	0.5
Luxembourg	0.3	0.4	0.6	0.5	0.8	0.5	0.5
Hungary	0.4	0.4	0.4	0.5	0.4	0.5	0.5
Malta	0.2	0.1	0.2	0.2	0.4	0.3	0.2
Netherlands	1.0	1.0	1.1	1.2	1.1	1.1	n.d.
Austria	0.9	0.8	0.8	0.8	1.0	1.0	0.8
Poland	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Portugal	1.0	1.1	1.0	1.1	1.0	1.1	1.0
Romania	1.0	0.7	0.8	0.5	0.4	0.4	0.4
Slovenia	2.1	1.9	2.0	8.4	0.9	1.0	1.0
Slovakia	1.2	1.2	1.1	1.1	1.0	0.8	0.9

Table 5. Completed PhDs**,** number of women per 1000 inhabitants (n.d. – no data). Source: Eurostat (continuation from p.772).

Country / Year	2013	2014	2015	2016	2017	2018	2019
Finnish	1.4	1.5	1.5	1.5	1.4	1.4	1.3
Sweden	1.3	1.4	1.3	1.2	1.2	1.1	1.0
Island	0.6	1.1	0.8	1.0	0.9	0.7	0.9
Liechtenstein	1.5	0.9	1.3	2.2	2.2	1.5	1.5
Norway	1.1	1.0	1.0	1.0	1.0	1.0	1.1
Switzerland	1.5	1.5	1.5	1.5	1.6	1.6	1.7
United Kingdom	1.4	1.3	1.4	1.4	1.5	1.5	1.6
North Macedonia	0.4	0.3	0.4	0.3	0.4	0.4	0.4
Serbia	n.d.	0.4	0.6	0.6	1.0	0.6	0.5
Turkey	n.d.	0.2	0.2	0.2	0.2	0.3	0.3

Total number of completed female PhDs per 1000 population from 25 to 34 years

From 2013 to 2019, the number of women's PhDs increased in Bulgaria, Greece, France, Hungary, Switzerland, and Turkey, while in Italy and Sweden, the number of women earning PhDs decreased over time. Between 2013 and 2020, the European Union average of 28 countries seems to have maintained a steady trend in terms of the number of women with doctorates, as well as in the Czech Republic, Austria and North Macedonia. According to the data, there are significantly fewer female PhD students in Bulgaria (0,3 women aged 25-34 per 1000 population), Greece (0,3 women aged 25-34 per 1000 population), Croatia (0,3 women aged 25-34 per 1000 population), Latvia (0,1 women aged 25-34 per 1000 population), Lithuania (0,3 women aged 25-34 per 1000 population), Hungary (0,3 women aged 25-34 per 1000 population), Malta (0,1 women aged 25-34 per 1000 population), Poland (0,3 women aged 25-34 per 1000 population), Romania (0,2 women aged 25-34 per 1000 population), North Macedonia (0,1 women aged 25-34 per 1000 population), Serbia (0,2 women aged 25-34 per 1000 population) and Turkey (0,2 women aged 25-34 per 1000 inhabitants) compared to Germany (1,1 women aged 25-34 per 1000 inhabitants) and Switzerland (1,3 women aged 25-34 per 1000 inhabitants).

Table 6. Completed PhDs**,** number of women aged 25-34 per 1000 population (n.d. – no data). Source: Eurostat (continued on p.774).

Country / Year	2013	2014	2015	2016	2017	2018	2019
EU - 27 countries (as of 2020)	n.d.	n.d.	0.6	0.7	0.6	0.6	0.6
EU - 28 countries (2013-2020)	0.6	0.6	0.7	0.7	0.7	0.7	0.6
Belgium	0.6	0.6	0.6	0.8	0.7	0.7	0.7
Bulgaria	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Czech Republic	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Danish	0.8	1.0	1.0	0.9	0.9	0.9	0.9
Germany	1.0	1.1	1.0	1.0	1.0	1.0	1.0
Estonia	0.5	0.3	0.3	0.4	0.5	0.4	0.4
Ireland	0.7	0.9	0.6	0.8	0.7	0.7	0.8
Greece	0.2	0.2	0.2	0.3	0.3	0.3	0.3
Spain	0.5	0.5	0.6	0.7	0.7	0.9	0.6
France	0.5	0.5	0.5	0.5	0.6	0.6	0.6
Croatia	0.4	0.4	0.5	0.3	0.3	0.3	0.3
Italy	0.6	0.6	0.6	0.6	0.6	0.5	0.5
Cyprus	0.2	0.2	0.2	0.3	0.2	0.3	0.3
Latvia	0.2	0.3	0.3	0.2	0.1	0.1	0.1

Table 6. Completed PhDs**,** number of women aged 25-34 per 1000 population (n.d. – no data). Source: Eurostat (continuation from p.773).

Country / Year	2013	2014	2015	2016	2017	2018	2019
Lithuania	0.5	0.4	0.4	0.3	0.4	0.4	0.3
Luxembourg	0.3	0.3	0.5	0.4	0.7	0.5	0.4
Hungary	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Malta	0.1	0.0	0.1	0.1	0.2	0.2	0.1
Netherlands	0.8	0.9	0.9	1.0	0.9	0.9	n.d.
Austria	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Poland	0.3	0.2	0.3	0.3	0.2	0.3	0.3
Portugal	0.4	0.4	0.4	0.5	0.4	0.4	0.4
Romania	0.6	n.d.	n.d.	n.d.	n.d.	0.2	0.2
Slovenia	1.4	1.1	1.1	2.5	0.6	0.6	0.5
Slovakia	1.0	1.0	0.9	0.9	0.7	0.7	0.6
Finnish	0.5	0.6	0.6	0.6	0.5	0.5	0.5
Sweden	0.7	0.7	0.6	0.6	0.6	0.5	0.5
Island	0.3	0.5	0.2	0.4	0.3	0.3	0.4
Liechtenstein	1.1	0.6	0.6	1.3	1.3	0.9	0.6
Norway	0.5	0.5	0.4	0.4	0.4	0.4	0.5
Switzerland	1.1	1.2	1.2	1.2	1.2	1.2	1.3
United Kingdom	0.9	0.8	0.9	0.9	0.9	0.9	0.9
North Macedonia	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Serbia	n.d.	0.1	0.2	0.3	0.3	0.3	0.2
Turkey	n.d.	0.1	0.1	0.2	0.2	0.2	0.2

ANALYSIS OF THE HOMOGENEITY OF LIFELONG LEARNING IN SELECTED EUROPEAN COUNTRIES

Description of data

Table 7 provides an overview of the variables used in the analysis, along with their abbreviations, descriptions, and their measurements. A total of seven variables were used to determine the number of units with homogeneous characteristics. Data were collected from the Eurostat database for 2019 for 35 European countries, including the Czech Republic, Ireland, Spain, France, the Netherlands, Austria, Portugal, Slovenia, Slovakia, Finland, Sweden, Iceland, Norway, Estonia, Greece, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Poland, Romania, North Macedonia, Serbia, Turkey, Denmark, Germany (former FRG territory until 1990), Liechtenstein, Switzerland and the United Kingdom.

Table 7. Variable names.

Abbreviation	Description of the variable	Measurement
ALL	Number of PhD graduates	Per 1000 inhabitants
25_34	Number of PhD graduates aged 25 to 34	Per 1000 inhabitants
M_ALL	Number of male PhD graduates	Per 1000 inhabitants
M_25_34	Number of male PhD graduates from 25 to 34 years	Per 1000 inhabitants
F_ALL	Number of female PhD graduates	Per 1000 inhabitants
F_25_34	Number of female PhD graduates aged 25 to 34	Per 1000 inhabitants
GDP_pc	GDP per capita	Per 1000 inhabitants

Table 8 presents the variables included in the analysis and their descriptions. Based on these variables, K-means was used for the grouping procedure.

Table 8. Variable descriptions.

Abbreviation	Variable	Description
ALL	PhD Graduates (per 1000 inhabitants)	The number of individuals who have completed a PhD normalised per 1000 people in the total population.
25_34	PhD Graduates (per 1000 population, aged 25-34 years)	The number of PhD graduates among people aged 25 to 34 is normalised per 1000 individuals in that age group.
M_ALL	PhD Graduates (per 1000 inhabitants, men)	The number of men who have completed a PhD normalised per 1000 men in the total population.
M_25_34	PhD Graduates (per 1000 population, aged 25-34 years, men)	The number of male PhD graduates aged 25 to 34 normalised per 1000 men in that age range.
F_ALL	PhD Graduates (per 1000 population, women)	The number of women who have completed a PhD normalised per 1000 women in the total population.
F_25_34	PhD Graduates (per 1000 population, aged 25-34 years, women)	The number of female PhD graduates aged 25 to 34 normalised per 1000 women in that age group.
GDP_pc	GDP per capita	GDP per capita in 2019 in EUR

Descriptive analysis

A total of seven variables were used for the analysis, Table 9. It contains the results of descriptive statistics of variables. It should be noted that the analysis used data from 2019 for 35 European countries. The median and mean were used as measures for the central tendency. The mean value of the variables ranges from 0,49 for PhD students in the age group from 25 to 34 years is 1,76 for the total number of PhD graduates for 2019 and the average GDP per capita of 40 775,47.

Furthermore, it can be observed that the mean values for all variables are lower than the mean values, suggesting that the data is skewed to the right. The coefficient of variation for the dataset includes a high value of 84,45 for GDP per capita and a lowest value of 46,51 for the total number of female doctors. Furthermore, the standard deviation ranges for the dataset range from 0,28 for female PhD graduates within the 25-34 age group and 1,05 for the total number of PhD students.

The minimum value of data for the observed variable ranges from 0,10 for male doctoral students in the age group 25-34 years and 1,30 for the total number of female graduates in the age group 25-34 years, while the minimum value of data for GDP per capita is 6 070,40.

On the other hand, it can be noted that the maximum value of the data ranges from 1,30 for female graduates aged from 25 to 34 and 5,70 for the total number of graduates in 2019. The maximum value for GDP per capita is 175814,00. The values for the lower and upper quartiles are also shown in Table 9.

The Pearson correlation matrix for the six observed variables is shown in Table 10. Scattering diagrams of the research variables are shown in Figure 1.

Table 9. Results of descriptive statistics for seven observed variables, $n = 35$, data from 2019.

Indicator	Variable						
	ALL	25_34	M_ALL	M_25_34	F_ALL	F_25_34	GDP_PC
Average	1.76	1.06	0.94	0.57	0.83	0.49	40775.47
Median	1.70	1.00	0.90	0.50	0.80	0.50	29555.30
Standard deviation	1.05	0.64	0.71	0.39	0.39	0.28	34435.42
Coefficient of variation	59.77	60.42	75.85	68.88	46.51	56.77	84.45
Skewness	1.71	0.88	2.96	0.92	0.46	0.91	2.14
Kurtosis	4.71	0.52	12.48	0.43	-0.46	0.86	6.11
Minimum	0.50	0.20	0.20	0.10	0.20	1.30	6070.40
Maximum	5.70	2.90	4.20	1.60	1.70	1.30	175814.00
Lower quartile	0.90	0.50	0.50	0.20	0.50	0.30	17926.80
Upper quartile	2.20	1.40	1.20	0.80	1.10	0.60	51939.00

Table 10. Pearson correlation matrix, $h = 6$ variables, $n = 35$ European countries.

	ALL	25_34	M_ALL	M_25_34	F_ALL	F_25_34
ALL	1					
25_34	0.8474***	1				
M_ALL	0.9701***	0.7708***	1			
M_25_34	0.8997***	0.9834***	0.8525***	1		
F_ALL	0.9066***	0.8745***	0.7795***	0.8685***	1	
F_25_34	0.7343***	0.9627***	0.6122***	0.9091***	0.8537***	1

***statistically significant correlations at the significance level of 1 %

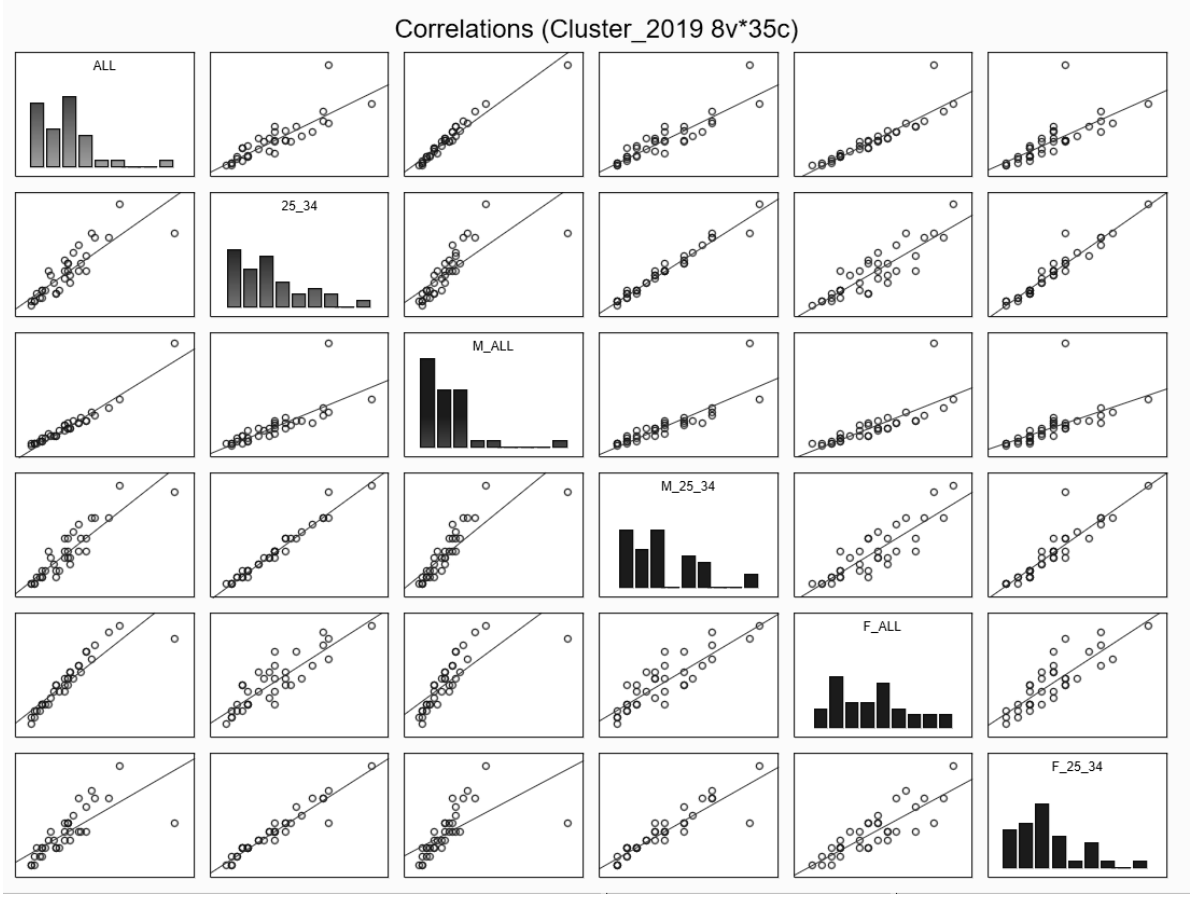

Figure 1. Scattering diagram of observed variables.

The correlation matrix presents significant associations between PhD graduation rates across different demographic groups. Notably, the correlation between PhD graduates in the total population and those aged 25-34 (r = 0,8474***) suggests a strong alignment between overall PhD trends and the younger age cohort. A similar pattern is observed between male and female PhD graduates, with high correlations both in the total population (r = 0,9066***) and within the 25-34 age group (r = 0,8537***). However, the relatively lower correlation between male PhD graduates (M_ALL) and female graduates aged 25-34 (r = 0,6122***) hints at potential gender-specific dynamics in the younger cohort, warranting further investigation into gender disparities. Additionally, the strong correlation between PhD graduates among younger men and women (r = 0,9091***) reflects consistent patterns of educational attainment in the 25-34 age group, suggesting that trends in male and female PhD graduation rates within this cohort are closely related. Overall, these findings highlight both the similarities and nuanced differences across demographic segments in PhD attainment.

k-Means cluster analysis

Statistical non-hierarchical cluster analysis was used to group the observed countries. A k-mean grouping algorithm was used. The greatest average distance technique was used to obtain the first centroids or estimates. The new centroids were calculated using all the analysed countries assigned to them after all countries were assigned to the nearest centroid. Euclidean square distances were used as a measure of distance to give more weight to countries that were farther away from the centroid [23].

This grouping technique has been carried out 50 times. However, it should be noted that before any calculations, the variables are normalised individually using the built-in data normalisation feature in the computer software. The minimum and maximum values of the observed variables, as well as the data, are translated into a predefined range during the normalisation process. As a result, the accuracy of clustering algorithms increases, thereby improving the ability to establish high-quality clusters [24].

The rule of thumb [25], cross-checking, the elbow technique, access to information criteria [26], and kernel matrix [27] are just a few of the ways to find the exact number of clusters. Due to the limitations of the computer program used (Statistica), the final number of clusters will be determined using the v-fold cross-check procedure.

The cost sequence graph, shown in Figure 2, reveals that the three-cluster solution is the best. The cost sequence graph shows the error function for different cluster solutions, which is defined as the average observation distance in subsamples to the cluster's assigned hubs [28]. Variations in cluster costs or errors between solutions with two to three clusters are considered significant. In other words, as the number of clusters increases, the error decreases by more than 5 % compared to a cluster solution with one cluster less. On the other hand, the error difference between solutions with two and three clusters is less than 5 %. As a result, a three-cluster solution was chosen as the best option.

The ANOVA analysis for 3 clusters shows that the null hypothesis is rejected at the 1 % level, showing that the solution of using 3 groups is appropriate, Table 11.

Table 12 shows the mean values of clusters of research variables, while Figure 3. It shows the distribution of research variables among clusters.

The mean values of the studied variables in clusters are shown in Figure 3.

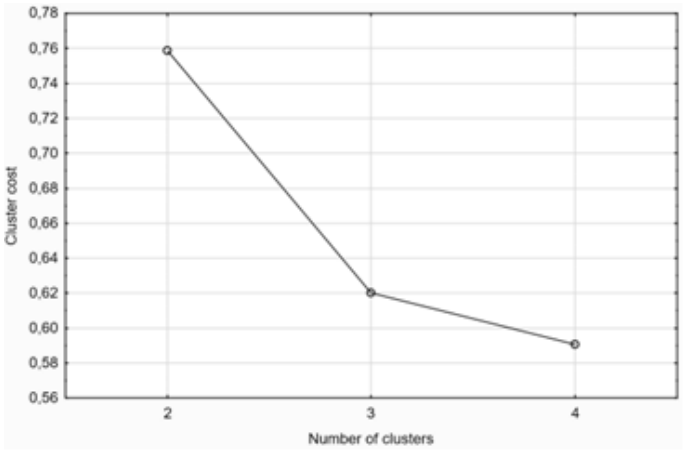

Figure 2. Cost sequence chart.

Table 11. ANOVA analysis, k-mean grouping, h = 6 variables, k = 3 clusters, n = 35 European countries.

	Between SS	Df	Within SS	Df	F	p-value
ALL	28.814	2.000	8.691	32.000	53.044	0.000
25_34	11.424	2.000	2.520	32.000	72.550	0.000
M_ALL	11.143	2.000	6.141	32.000	29.035	0.000
M_25_34	4.239	2.000	0.976	32.000	69.504	0.000
F_ALL	4.098	2.000	1.021	32.000	64.221	0.000
F_25_34	1.905	2.000	0.710	32.000	42.944	0.000

Table 12. Average values by cluster, cluster analysis of k-mean values, h = 6 variables, n = 35 European countries, 2019.

	Cluster 1	Cluster 2	Cluster 3
ALL	2.00	0.96	3.64
25_34	1.24	0.54	2.22
M_ALL	1.04	0.47	2.16
M_25_34	0.67	0.26	1.28
F_ALL	0.98	0.51	1.48
F_25_34	0.58	0.27	0.94
Number of cases	14	16	5
age, %	40.00	45.71	14.29

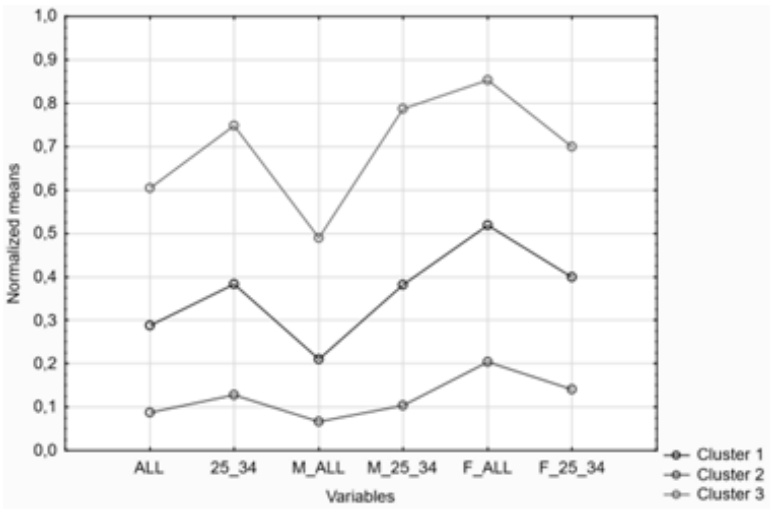

Figure 3. Average values of research variables by cluster.

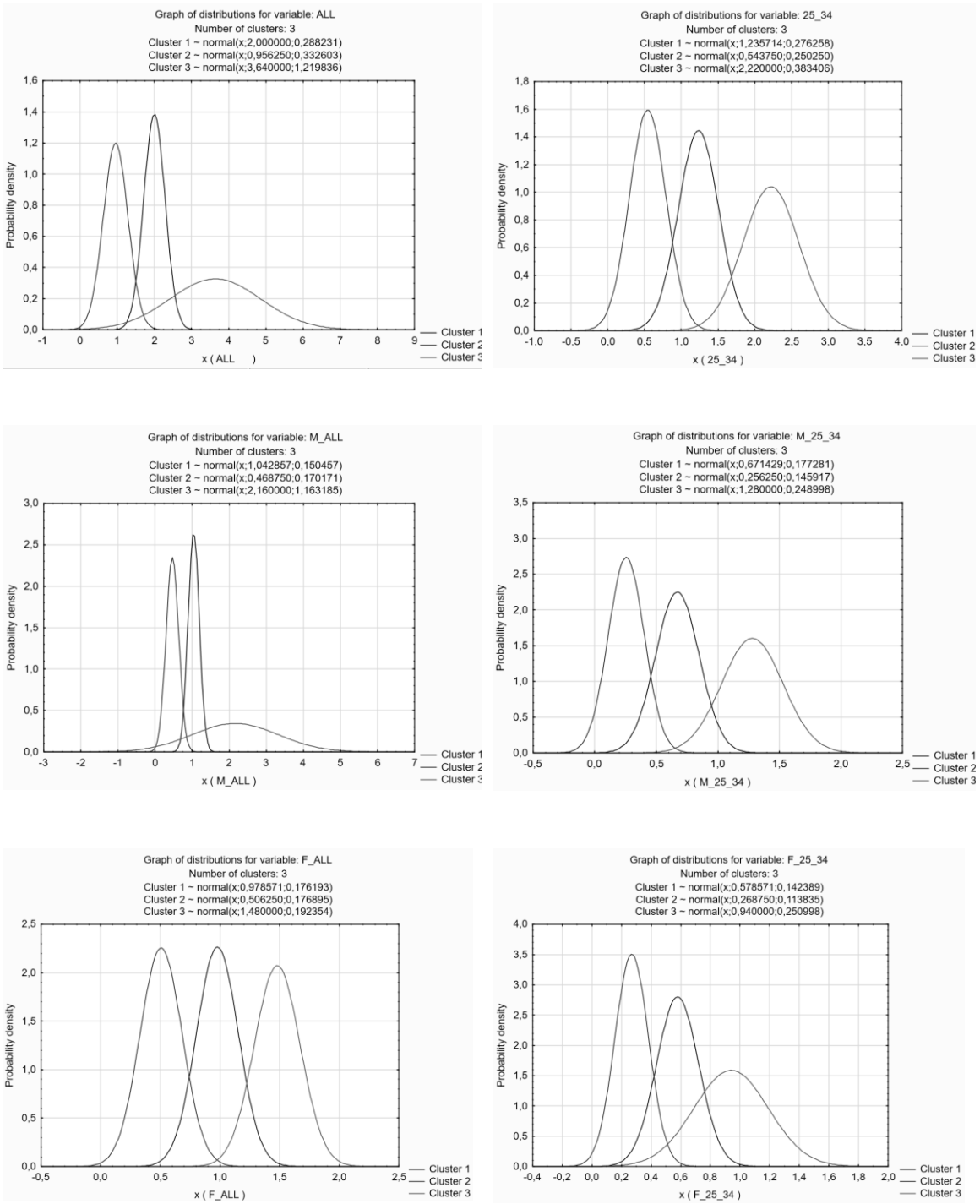

Figure 4. Distribution of research variables by cluster.

Figure 3 shows the distributions of all six observed research variables for the analysed countries. Distributions can be used to observe the degree to which countries differ in a cluster based on the observed variable. The smaller the gap between countries, the narrower the distribution. Knowing the probability density function for a sample of data can help us determine whether a particular observation is plausible or so unlikely that it can be labelled extraordinary or anomalous and should be ruled out. It is quite useful for selecting acceptable learning methods that require certain probability distributions in the input data.

This study uses data from 2019 for cluster analysis for 35 European countries. According to the factors studied, we found three groups with significant differences: the total number of doctoral graduates per thousand inhabitants, the total number of doctoral graduates aged 25 to

34 per thousand inhabitants, the total number of male graduates at the doctoral level per thousand inhabitants, the total number of male graduates at the doctoral level aged 25 to 34 per thousand inhabitants, the total number of female graduates at the doctoral level per thousand inhabitants and the total number of female graduates aged 25 to 34 per thousand inhabitants.

Table 13 lists the countries by cluster, and the Western Balkan countries fall into groups C1 and C2. Cluster 1 consists of 13 countries, including the Czech Republic, Ireland, Spain, France, Netherlands, Austria, Portugal, Slovenia, Slovakia, Finland, Sweden, Iceland, and Norway. The countries belong to different geographical regions such as Scandinavia (Iceland, Norway, Sweden, and Finland), Central Europe (Austria, Czech Republic, Slovakia), Southeastern Europe (Slovenia), Southern Europe (Portugal, Spain), Western Europe (France, Netherlands), and Northwestern Europe (Ireland). This cluster is the most diverse with regard to the geographical position of the countries. All countries are members of the EU. To improve the quality and openness of EU Member States' education and training systems, the European Union has two types of instruments: a set of policy instruments that encourage EU countries to develop their education systems and learn from each other's successes and a significant programme to support exchanges, networks and mutual learning between schools, universities or training centres, as well as between political authorities.

Cluster 2 consists of 15 European countries: Estonia, Greece, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Poland, Romania, North Macedonia, Serbia, and Turkey. Six countries belong to the Western Balkans (Greece, Croatia, Cyprus, Romania, North Macedonia, Serbia and Turkey). The levels of educational achievement in the countries of this region are different. Despite the fact that the Balkans have experienced multiple conflicts in recent years, they have made progress towards democratic societies and improved their economic infrastructure. However, there are still countries with flawed democracies and those with thriving economies where gains in terms of basic freedoms, the rule of law and democratic governance are not yet durable or irreversible. The EU's capacity to convey democracy through its enlargement agenda is failing to deliver on its promise to give democracy to these countries in the EU accession process (North Macedonia, Serbia and Turkey), and the area is becoming increasingly vulnerable to authoritarian governments.

Furthermore, this cluster includes countries from the Baltic Sea region (Estonia, Latvia and Lithuania), known as the "Baltic states". The key goals of the three countries are to establish a free and open market economy, to open up globally within the EU, to reform science and research, and to increase innovation. The Baltic countries have significantly changed their economies and scientific systems in the years since independence, gaining full membership in the European Union. Other countries in this cluster belong to Central Europe (Hungary and Poland), South-Central Europe (Italy) and the Mediterranean region of Europe (Malta). All these countries are members of the EU. This cluster shares similar characteristics and the lowest level of educational achievement compared to Cluster 1 and Cluster 3.

Cluster 3 has the highest level of cluster mean, as shown in Figure 4. The most distinctive attribute of this cluster is the highest total number of PhD graduates in 2019 compared to other clusters. This cluster consists of five European countries: Denmark, Germany (until 1990, the former territory of the FRG), Liechtenstein, Switzerland, and the United Kingdom. These countries belong to the Northwest Europe region; that is, this cluster includes economies from Northern Europe (Denmark and the United Kingdom) and Western Europe (Germany and Switzerland), with the exception of Liechtenstein. Compared to other OECD countries, educational achievement in Northern and Western Europe is quite high. Most countries in the area are democratic welfare states with a government that provides a wide range of social services and benefits. This region is known for its high level of organisational flexibility and civic involvement, as well as its philanthropic political climate.

Table 13. Countries by Clusters**.** Source: author's research based on Eurostat data from 2019.

Cluster	Countries
C1	Czech Republic, Ireland, Spain, France, Netherlands, Austria, Portugal, Slovenia, Slovakia, Finland, Sweden, Iceland, Norway
C2	Estonia, Greece, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Poland, Romania, North Macedonia, Serbia, Turkey
C3	Denmark, Germany (former FRG territory until 1990), Liechtenstein, Switzerland, United Kingdom

Figure 5 shows a European map by country grouped into specific clusters based on PhD-level graduates by country: 2019.

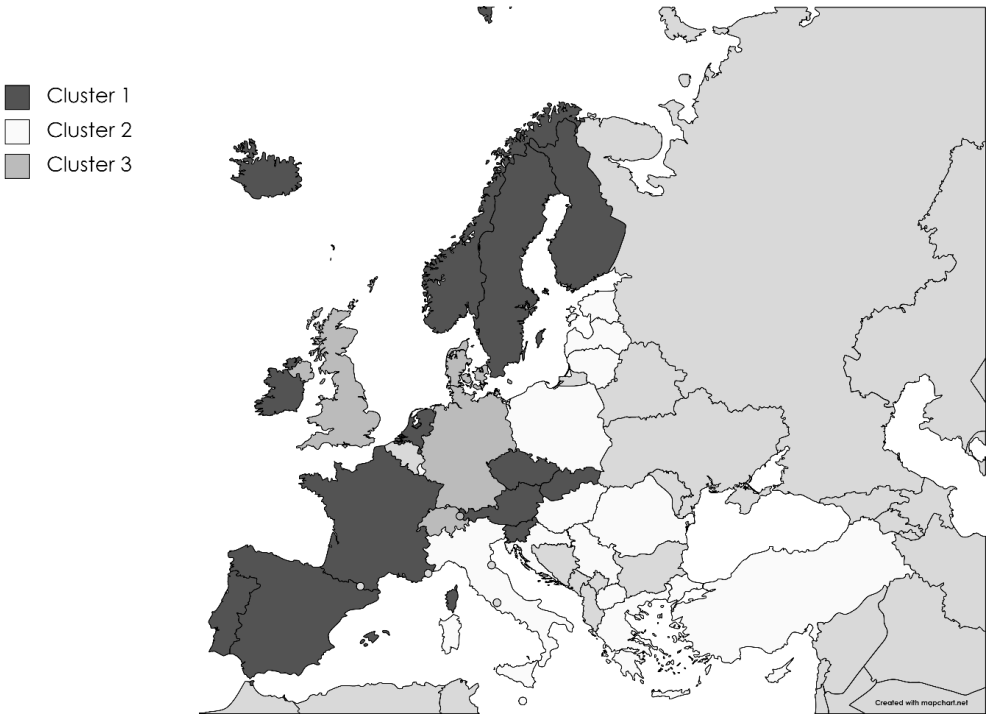

Figure 5. European map by country grouped in specific clusters based on PhD-level graduates by country; 2019.

This section presents the results of the ANOVA analysis and an indicative group-by-group diagram for GDP per capita by cluster, Table 14.

We estimated the average GDP per capita values for each cluster to examine the relationship between educational achievement and the level of economic growth of the selected European countries surveyed in 2019, Table 14. Cluster 3, which was the most developed in terms of educational indicators, was also the most developed in terms of average GDP per capita (USD 82 157,2) as a result of the grouping of the most developed European countries (Denmark, Germany (until 1990 the former territory of the FRG), Liechtenstein, Switzerland and the United Kingdom) into this cluster. On the other hand, Cluster 2 had the lowest average GDP per capita ($23 657,90), which was also the lowest in terms of lifetime educational metrics. A similar relationship exists for the percentage change in GDP. The Kruskal-Wallis test suggests that the variation in medians reported for the three clusters identified is not statistically significant, indicating a strong association between economic growth and educational achievement in the observed European countries.

The results of the ANOVA analysis, as well as the box-plot diagram by groups for GDP per capita by cluster, are shown in Table 14 and Figure 6.

Table 14. Average value of GDP per person by cluster; ANOVA analysis. Mean values and standard deviations (in parentheses) are given; bold letters indicate the highest average value.

	Projects	N	Std.Dev.	F-test	p-value
C1	45558,96	14	19922,35	8,118	0,001***
C2	23657,90	16	25199,86		
C3	82157,92	5	54911,03		
Total	40775,47	35	34435,42		

***significant at the level of 1 %

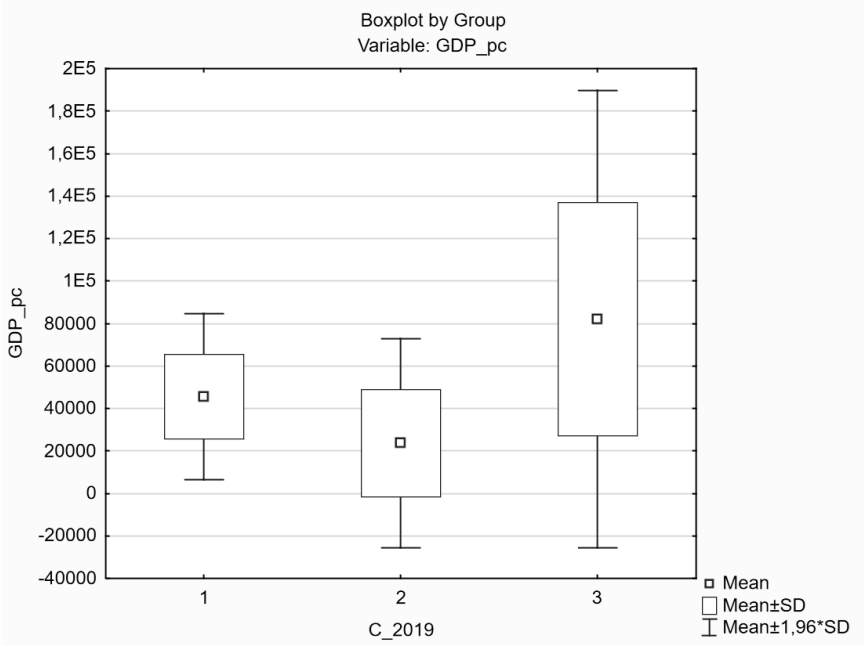

Figure 6. Box plot diagram of GDP per person by cluster.

Post hoc analysis was used to observe the levels of educational achievement in which groups of countries differ significantly in educational parameters, Table 15. For this purpose, the post hoc Fisher comparison of the least significant difference (LSD) is used. The primary principle of LSD is to calculate the lowest significant difference (i.e. LSD) between the two mean values as if they were the only means of comparison (i.e., use on the test) and declare any difference greater than LSD significant. Only certain pairs that are statistically significant at the 10 % level (six pairs) are given in the table. The table also shows the mean % difference between the groups. We can determine that the most significant difference occurs in most cases between cluster 2 and cluster 3 (2 pairs), followed by cluster 3 and cluster 1 (2 pairs). The same number of pairings is shown between Cluster 1 and Cluster 2. From here, we can reasonably conclude that cluster 3 (Denmark, Germany (former FRG area until 1990), Liechtenstein, Switzerland and the United Kingdom) has the highest levels of lifelong learning uptake, while the other countries analysed lag behind. This finding implies that the development gap between the European countries studied will remain unchanged, if not widened, unless serious efforts are made to improve educational achievement in the countries.

It can be concluded that the cluster analysis data confirmed that there are significant differences between European countries regarding the implementation of lifelong learning in 2019 and that these differences are related to economic development. Finally, the differences are statistically significant between individual clusters, as shown by the post-hoc analysis, confirming that there is a strong heterogeneity in European countries with regard to the implementation of lifelong learning. The limitation of this analysis arises from the fact that only one year has been analysed, and the analysis should be repeated for a longer period to confirm the results presented.

Table 15. Post-hoc LCD Cluster Difference Comparison Test.

	(I) C_2019	(J) C_2019	Mean Difference (I-J)	Std. Error	Mr.
LSD	C1	C2	21901.06	10580.15	0.047**
		C3	-36598.96	15062.01	0.021**
	C2	C1	-21901.06	10580.15	0.047**
		C3	-58500.02	14812.21	0.000***
	C3	C1	36598.96	15062.01	0.021**
		C2	58500.02	14812.21	0.000***

**significant at the level of 5 %
*** significant at the level of 1 %

DISCUSSION

Lifelong learning has become increasingly important in the fields of economics, business, and management, as highlighted in recent research. Laal and Salamati [29] support the notion that lifelong learning is essential for personal and professional development, arguing that it enables individuals to stay competitive in an ever-changing labour market. Lifelong learning has become increasingly important in the fields of economics, business, and management, as highlighted in recent research. Vrdoljak [30] further emphasises the growing need for continuous education to adapt to the evolving demands of the global economy, with a focus on the benefits of lifelong education for professionals in these fields. Lifelong learning has recently been supported by e-learning. In the context of e-learning, Głodowska et al. [31] discuss the pros and cons of digital education in economics and business, noting its increased relevance during the COVID-19 pandemic. Their cross-country study in Central and Eastern Europe reveals that while e-learning offers flexibility and accessibility, it also presents challenges, such as the digital divide and varying levels of engagement. Mališ Sever et al. [32] explore the landscape of e-learning during the pandemic in Croatia, focusing on economic disciplines. Their findings indicate that while the shift to online education provided a necessary solution, it also raised questions about the quality and effectiveness of learning in virtual environments. Both researches [31, 32] indicate that e-learning has a significant potential as a leverage for increasing lifelong learning.

This research is a continuation of the research conducted by Vrdoljak in 2023 [33]. Based on the conducted research on the development of lifelong learning in the countries of the European Union, a cluster analysis was conducted that identified significant differences in educational achievements, especially at the doctoral level. The results show that Western and Northern European countries, such as Denmark, Germany, Switzerland and the United Kingdom, achieved the highest number of PhDs per capita. In contrast, Eastern and Southern European countries, including Greece, Croatia, and Romania, had significantly lower rates of PhD studies. Also, there are significant differences in the gender representation of doctoral students, whereby women are generally less represented than men, especially in the younger population.

These differences in educational achievements are closely related to the economic development of countries, with more economically developed countries having a greater number of doctoral students and more developed lifelong learning systems. These results highlight the need to strengthen education and lifelong learning systems in less-developed European countries in order to reduce the educational achievement gap and promote economic and social inclusion. Therefore, strategic policies that encourage education, research and development, especially at the doctoral level, are key to achieving long-term economic growth and social cohesion throughout the European Union.

Based on the conducted research on the development of lifelong learning in the countries of the European Union, using K-means cluster analysis, significant differences in educational achievements among EU countries were identified, with a special emphasis on doctoral education. The analysis classified the countries into three clusters. The first cluster, which includes countries such as the Czech Republic, Ireland, Spain, and the Netherlands, is characterised by moderate educational achievements. The second cluster, which includes countries such as Croatia, Italy, Poland and Romania, shows significantly lower educational results and lower rates of doctorates per capita. The third cluster, which includes economically developed countries such as Denmark, Germany, Switzerland and the United Kingdom, shows the highest rates of doctorates and the most developed lifelong learning systems. These differences between clusters clearly indicate the connection between economic development and the success of educational systems, with an emphasis on doctoral studies.

Cluster analysis has proven to be a useful method for grouping countries based on educational and economic variables, allowing the identification of similar educational patterns within the European Union. The results of the cluster analysis clearly indicate that countries with higher GDP per capita also have higher rates of doctorates, which confirms the importance of economic factors in the development of educational systems. The analysis also highlights regional differences between Western and Eastern Europe, whereby Western European countries, despite their geographic and economic diversity, show greater homogeneity in educational achievement. In contrast, Eastern European countries lag, partly due to less developed educational institutions and lower investment in research and development.

One of the key limitations of this study is the limited amount of available data, as the data for the cluster analysis refer to only one year (2019), which does not allow insight into long-term trends. Another limitation is that the focus is only on selected variables, such as the number of PhDs per capita and GDP per capita. In contrast, other important factors that may influence lifelong learning, such as political or social indicators, are not included in the analysis. Additionally, cluster analysis, although useful for grouping countries according to similarities, has its limitations in terms of classification precision and the possibility of some countries being misplaced into clusters.

Recommendations for future research are based on this study's limitations but also the identified opportunities for a deeper understanding of the development of lifelong learning in Europe. First, future research should expand the time frame of analysis to allow monitoring of long-term trends. By analysing data over several years, it is possible to identify changes in educational systems, determine the factors that contributed to these changes, and observe how different economic and political situations affect the development of doctoral education and lifelong learning [34].

It is also recommended to include additional variables that can provide a broader picture of the factors that influence educational achievements. For example, variables such as political stability, investment in research and development, social equity, and social and cultural policies may play an important role in shaping education systems and should be further explored. These variables can provide deeper insights into how social and political contexts within individual countries affect educational outcomes.

Expanding the sample of countries is also an important recommendation. Although this study covered 35 European countries, the inclusion of countries outside of Europe could offer a wider international context and enable a comparison between European and non-European education systems. This would enable the understanding of global educational trends and could contribute to the development of better strategies for lifelong learning at the global level.

Finally, it is recommended that quantitative and qualitative research methods be combined. Although cluster analysis provides valuable statistical insights, qualitative methods, such as

interviews with policymakers, experts and education workers, can provide a deeper understanding of specific challenges and opportunities within education systems. Such an approach would enable a holistic overview of the problem and could help in designing concrete and adapted solutions to encourage the development of doctoral education and lifelong learning.

CONCLUSION

In conclusion, this study underscores the critical importance of lifelong learning and doctoral education in fostering economic development and social inclusion across the European Union. The findings highlight significant disparities in educational achievements, particularly in doctoral education, between economically developed Western European countries and less-developed Eastern European counterparts. These disparities are closely linked to economic factors, with countries having higher GDP per capita demonstrating more advanced lifelong learning systems and higher doctoral completion rates. While considering these findings, it has to be considered that the progress of each doctoral student is based on sufficient funds, salaries, opportunities, scholarships, and other resources useful for research and the creation of a standard of living, as well as on the commitment and work invested in study and research. PhD students in Western Europe have greater opportunities to publish, participate in conferences and workshops, and improve their academic position than PhD students in Eastern Europe. From here, it is important to note that universities should address the social and economic needs of individuals who are technologically and informationally literate while enhancing students' language abilities to increase interest in pursuing a doctorate. In addition, universities should learn to adapt to an ever-changing environment where students must learn to adapt instead of studying solid and solid information.

The cluster analysis provides valuable insights into educational patterns within Europe, emphasising the need for tailored strategic policies to strengthen education systems in less-developed regions. Addressing these disparities requires increased investment in research, development, and support systems for doctoral students, alongside initiatives that enhance access, equity, and adaptability in education. Future research should focus on expanding the scope and depth of analysis, incorporating additional variables such as political, social, and cultural factors, and extending the geographic and temporal range of studies. Combining quantitative and qualitative approaches will offer a more comprehensive understanding of the challenges and opportunities in promoting lifelong learning and doctoral education globally.

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