THE NEED FOR ARTIFICIAL INTELLIGENCE IN SUSTAINABLE CONSTRUCTION

Abstract

This article presents an analysis of the role of artificial intelligence (AI) in implementing sustainable innovations in the construction sector. The author discusses the definitions, types, and applications of AI, emphasizing its importance in optimizing design processes, energy management, and automating construction tasks. Empirical research conducted on a sample of 130 companies and 732 employees revealed statistically significant correlations between the demand for AI and employee education and age. The results confirmed that younger and more highly educated individuals demonstrate greater readiness to implement AI in their professional practice. The article indicates that AI is a key factor supporting the achievement of sustainable development goals by increasing energy efficiency, reducing operating costs, and improving the quality of the working environment. The conclusion emphasizes the need for integrating digital competencies among engineering staff and an ethical approach to implementing AI technologies in construction.

INTRODUCTION

In an era of dynamic technological development, artificial intelligence is becoming one of the most important tools supporting the implementation of sustainable development. Its application in various sectors of the economy, including construction, opens up new possibilities for optimizing design processes, improving energy efficiency, and minimizing the negative impact of investments on the environment.

Sustainable construction requires the integration of modern technological solutions that enable more rational resource management, reduced emissions, and the creation of people-friendly spaces. In this context, artificial intelligence serves as a catalyst for innovation-supporting data analysis, automating decision-making processes, and enabling the design of intelligent and energy-efficient buildings.

This article aims to examine the relationship between the development of artificial intelligence and the implementation of sustainable innovations in the construction sector. The analysis encompasses both theoretical aspects of AI's operation and empirical research findings, which indicate the growing importance of digital competencies among industry employees. The author focuses on two key application areas: generating sustainable building designs and automating construction tasks. The research findings allow us to determine which demographic and educational factors determine the degree of openness to AI technologies in sustainable development processes.

The aim of the study is to show the potential of artificial intelligence as a tool for transforming the construction sector towards efficiency, innovation and environmental responsibility.

The article consists of five parts. Part one discusses artificial intelligence, its nature, types, benefits, and concerns related to its implementation, as well as the ethical and legal framework. Part two addresses sustainable innovations in construction as innovations in the form of sustainable development tools using artificial intelligence. Part three examines the correlations between sustainable innovations in construction and the development of artificial intelligence. The research procedure, methods, techniques, and research tools, along with selected statistical methods, are presented. This is followed by a statistical analysis of the research results on generating sustainable building designs and automating construction tasks in sustainable construction. A summary of the research results is followed by a brief discussion.

1. ARTIFICIAL INTELLIGENCE

New technologies play a crucial role in shaping today's everyday life. One of the revolutionary achievements of recent years is artificial intelligence, which is integrating into numerous areas of life, such as industry, medicine, entertainment, and communications. New technologies open up limitless possibilities while posing challenges related to security, privacy, and ethics.

1.1. The essence of artificial intelligence

The concept of "artificial intelligence" (AI) was first formulated by J. McCarthy in 1955, during a conference in Dartmouth devoted to the application of this concept [1, p. 438]. Subsequently, artificial intelligence became the subject of ongoing debate. D. Partridge [2, p. 1]noted that self-learning AI constitutes the beginning of a new, entirely separate legal entity, arguing that artificial intelligence is the name of any entity that will later have to function with it.

Most definitions of AI are subjective because their authors refer to human behavior. According to T. Zalewski [3, p. 6], artificial intelligence has no ability to learn or solve problems; it can only behave as if it were "thinking." T. Zalewski refers directly to the principle of AI, which involves simulating human thinking.

According to the European Commission [4], artificial intelligence is a system that exhibits certain characteristics of intelligent behavior by analyzing its environment and taking specific actions, partially autonomously, to achieve specific goals. While concise, this definition refers to intelligent behaviors that are not fully defined.

From a computer science perspective, artificial intelligence is treated as a device for analyzing large amounts of data, first categorizing it, finding patterns, and then making decisions based on it [3, p. 3]. Based on the analyzed data, such systems can learn and continue this learning during their operation. Decision-making is optimized, and the database is expanded. This is called weak artificial intelligence, in contrast to strong artificial intelligence [5, p. 419]. Weak artificial intelligence is the ability to act like a human. Strong AI, on the other hand, relies on actual thinking, i.e., thinking in a non-simulated manner. Many scientists argue that strong AI will never be created [3, p. 4].

Artificial intelligence uses algorithms in the form of a set of rules, usually designed to solve a specific problem. Additionally, software and algorithms should exhibit self-learning characteristics [6, p. 2]. Self-learning is achieved using programming techniques called machine learning (processing large amounts of data in real time) [7, p. 35].

For further considerations, the following definition of artificial intelligence was adopted: it is a system that allows for the performance of tasks that require learning and that should take into account new circumstances when solving a specific problem, and that can also operate autonomously and enter into various types of interactions with the environment.

1.2. Types of artificial intelligence

The following five types of artificial intelligence have been identified in the literature: artificial neural networks, GOFAI, evolutionary programming, dynamic systems and cellular automata [8, pp. 18-19].

Artificial neural networks are mathematical structures and their software models that enable complex mathematical calculations, utilizing so-called artificial neurons that perform operations on the model's input. These neurons are a simplified model of brain nerve cells, characterized by multiple input signals and a single output signal. Artificial neural networks are often described as interdisciplinary fields of knowledge that explore the capabilities of this type of network. An important feature of artificial neural networks is the ability to generalize, that is, organize knowledge results for new variables that have not previously been used in science (approximation of multivariable function values) [9, p. 6].

The GOFAI system was developed in 1950 by A. Turing [10], who published a paper on computing machines and intelligence. Since then, information processing has been considered a fundamental function of intelligence. The model of computation proposed by this author has been treated as a metaphor for the brain, perpetuating the belief that the human brain is a so-called "Turing machine" that performs calculations and controls human actions. The methods of this approach aligned with the contemporary perception of intelligence and assumed that intelligent actions result from the automatic manipulation of symbols operating on a set of stable representations [11, p. 113]. In connection with the GOFAI system, A. Newell [12, p. 119] has been accepted as saying that the most important discovery of artificial intelligence in computer science was the creation of a concept referring to a physical symbolic system, the same as that used by humans.

Evolutionary programming was introduced by L.J.Fogel [13], which was later called the genetic algorithm [14, p. 85]. This type of programming focuses on optimization problems with continuous parameters. Evolutionary programming uses an algorithm that uses only the mechanism of data selection and mutation, during which optimal solutions are selected [15, p. 284].

Dynamic systems are those that exhibit structural or functional changes over time [16, p. 178]. State-of-the-art computers are an excellent tool for modeling the dynamics of systems exhibiting chaotic behavior. Digitally modeled dynamic systems are only an approximation of certain boundary properties that emerge over infinite time intervals of system transformation. The greater the accuracy of the calculations, the better the approximation [17, pp. 403-404].

Cellular automata are discrete models used in physics, mathematics, and many computational theories. They are compositions of the same underlying cellular automata arranged in a grid (lattice). Their work involves obtaining a quantity of data as input and sending it to the cellular automata environment, which is then simulated to find the optimal output solution [18, pp. 270-271].

There are five important types of artificial intelligence, each with numerous mutations and applications. The GOFAI system, inspired by the work of A. Turing, is based on the automatic manipulation of symbols that reflect the functioning of the brain in the form of a Turing machine. Artificial neural networks, on the other hand, are mathematical structures that mimic the functioning of nerve cells, enabling pattern recognition and knowledge generalization. Evolutionary programming uses mutation and selection mechanisms to solve optimization problems. Cellular automata simulate phenomena in lattices of cells, seeking optimal solutions. Dynamic systems model time-varying phenomena.

1.3. Benefits and concerns of implementing artificial intelligence

Artificial intelligence, as a system capable of performing tasks that require learning and that should take into account new circumstances when solving a specific problem, and that can operate autonomously and interact with the environment in various ways, is a set of technologies that, with the help of machines, enable the augmentation of human potential. These machines can detect images, sounds, speech, text, understand, act, and learn [19, pp. 6-7].

The European Parliament Resolution [20, p. 239], which concerned robotics, noted that the development of artificial intelligence must reduce the environmental impact of harmful substances through efficient energy consumption, the use of energy from renewable sources, the generation of minimal waste, and the repairability of consumer goods. Furthermore, the use of robotics should also positively impact agriculture, food supply, reducing the size of machinery, and reducing the use of fertilizers, energy, and water [20, principle 47].

Artificial intelligence is relatively often used in medicine to compare images with databases (with patterns). This supports doctors' work, speeds up diagnosis, and reduces its error rate [21, pp. 58-59]. Artificial intelligence has been used to perform various functions that can assist people with disabilities, such as smart homes, voice assistants (recognizing unclear voices, providing weather information, setting reminders, alarm clocks, turning on lights, setting heating temperatures, and glasses for the blind) [21, pp. 59-60].

Concerns about implementing AI primarily concern jobs and the elimination of specific professions, disinformation, and loss of privacy, for example, the surveillance of citizens in China [21, pp. 61-63]. The costs associated with implementing AI cannot be precisely estimated because of the so-called Collingridge dilemma [22, p. 56], which means that the impact of new technologies can only be assessed after their implementation. Furthermore, the large scale of implementations makes them difficult to monitor, as practice shows that the larger the scope of a given phenomenon, the more difficult it is to monitor its costs.

1.4. Ethical and legal framework

An ethical approach to the development of artificial intelligence is a multi-stage process. B.C. Stahl [23, p. 26] distinguished the following three main problem areas regarding the ethical application of AI: the techniques used, the functioning of digital markets, and selected areas of philosophy and religion.

The legal framework for addressing AI challenges can be divided into those that address human responsibility for AI actions and those that determine AI's responsibility for actions towards humans [24, p. 278]. The European Union has addressed legal issues in this area, adopting a resolution on industrial policy for artificial intelligence and robotics in February 2019 [25, p. 5]. The EU is working towards creating an AI code to ensure that AI is trustworthy [26, p. 9].

All AI technologies are to be placed into the following four risk groups: unacceptable, high, limited, and minimal [27]. Unacceptable risks concern the following: obtaining biometric data in real time, classifying people, using subliminal techniques, exploiting vulnerabilities of individuals, conducting risk assessments of individuals, and acquiring untargeted facial recognition [27, Article 5]. High risks concern issues that negatively impact security as well as fundamental rights [27, Article 6].

Ethical issues stem primarily from the lack of transparency of algorithms, the risk of bias and distortion, and the potential impact of AI on society. Meanwhile, legal regulations have been developed to ensure trust in AI through the creation of codes and the classification of technologies according to risk levels.

2. SUSTAINABLE INNOVATIONS IN CONSTRUCTION

The concept of sustainable development has become a significant civilizational idea in Europe. General principles of sustainability were formulated by H.E. Daly [28, p. 31], who noted that raw materials should not be consumed in such a way that they cannot be replaced by renewable materials, and that waste should not be generated faster than nature can handle it (absorption, recycling, disposal). According to this author, sustainable development is expressed through the so-called sustainable development indicator (SSNP), which represents national product less the costs of cleaning up ecological damage. J. Kronenberg and T. Bergier [29, p. 76] define this phenomenon similarly.

2.1. Innovations in the form of sustainable development tools

Innovation is a comprehensive process characterized by interdependencies and mutual interactions between various actors who demonstrate the ability to learn and respond to emerging circumstances in a creative way [30, pp. 623-624]. According to A. Marszałek, it will be a process in which technology and the related industry using new patterns of operation contribute to the creation of a modified business model [31, p. 49]. G. Pisano [32, p. 82] distinguished the following four types of innovation:

- routine – using existing technical capabilities and fitting into the currently operating business structure (requiring large financial outlays),
- breakthrough – requiring the use of a new business model, but the existing technological base does not change (it is simple and accessible),
- radical – having a purely technological nature, there is no need to change the previously developed business model (they require significant changes in the product technology),
- architectural – constituting a conglomerate of changes taking place while modifying the business structure (the most complex form of innovation).

The innovation process is divided into two dimensions: a change in the functioning of the business model and a technological change. The strategy chosen depends on the company's technological resources and the business model being implemented [33, p. 25].

Sustainable development can be achieved through the use of economic processes so that durable and necessary high-quality products are created with low energy and raw material consumption and limited environmental pressure [34, p. 64]. Practical actions that will lead in this direction include: reducing the burden on the economy (saving raw materials, water, and energy); applying good management practices; shaping pro-ecological behavior patterns ; developing the environmental protection equipment industry; and creating a new value system based on preserving natural resources. Sustainable development can also mean balance in ecosystems and a balance between the economic, social, and ecological elements of economic development, i.e., social, spatial, and economic order [35, p. 18].

Sustainable development policy should lead to integrated solutions to various economic and environmental problems related to limited natural resources. Its main goal will be to modernize the economy through changes in the structure of industrial production, the creation of modern management systems, and the development of high-tech industries. Promoting such a development path will serve to strengthen the competitiveness of the knowledge-based economy and innovation [34, pp. 65-66].

Innovations in the form of sustainable development tools help optimize resource consumption, increase operational efficiency, reduce emissions, and create business models based on environmentally and socially conscious design. These include technologies such as digital (Internet of Things, cloud computing, artificial intelligence); energy (energy-efficient equipment, renewable sources); and process (waste-free technologies, closed-loop water systems, transparent supply chains) [36, p. 247].

2.2. Artificial intelligence in the innovation process

Widespread access to technological tools means that individuals or companies adopting new technologies derived from innovative activities improve existing solutions and develop good ideas [37, pp. 13-14]. Such behavior facilitates the creation of new products and simultaneously allows competitors to copy ideas and products. Financial success may therefore depend more on customer relationships and effective management than on technological progress, although in certain areas progress may play a more important role, as new systems strengthen the position of companies building their products on the basis of modern solutions. They must also accept the conditions set by system manufacturers, limiting their own freedom of action [38, p. 61].

Definitions of innovation include the following activities: all types of novelties, the implementation of new techniques and technologies, the creation of new organizations, as well as product innovations (products, services) and technological innovations, such as process innovations (new methods of implementation), organizational innovations, technological innovations, and institutional innovations [39, p. 11]. In construction, innovations are implemented primarily in structural, technological, and organizational solutions. They are regulated by international and national regulations.

Modern technologies and innovative solutions have become a permanent component of global business. Cloud computing platforms and the ability to connect manufacturing capabilities to implement shared business processes are gaining importance. Modern information technologies, such as artificial intelligence, determine the potential of organizations and the ability to introduce innovative solutions into business processes [40, 2023, p. 149]. The potential of AI has been recognized by enterprises, as well as by the healthcare, transport, and agricultural sectors. Government and EU guidelines also emphasize the importance of this topic. Implementing AI in various areas of the Polish economy is expected to increase the dynamics of innovation and GDP growth by approximately 2% annually [19, p. 8].

It's clear, then, that artificial intelligence is playing an increasingly important role throughout the innovation cycle. It's most commonly used for the following tasks:

- identifying problems and generating ideas: analysis of trends and social data (detection of niches and needs),
- generating new concepts (generative design, creating concept prototypes),
- analysis of competition and innovation to identify technical gaps,
- feasibility assessment (forecasting demand, prices and return on investment under various scenarios, scanning patents and publications),
- design and optimization (product architecture, shaping of engineering parts, optimization of parameters using machine learning techniques), simulations and modeling with improved predictive models),
- rapid prototyping and testing (automation of prototyping, generation of test variants, digital simulations, virtual testing, support in experiment planning and result analysis),
- validation and data-based decisions (analysis of clinical trial results or market tests with automatic detection of trends and anomalies),
- implementation and commercialization (offer and product personalization thanks to customer segmentation and recommendations, operational automation, process robotization, intelligent production lines, as well as supply chain optimization, support for pricing decisions and market entry strategies based on data analysis.

2.3. Artificial intelligence in the context of sustainable construction

The shortage of engineers and the growing demand for construction-related services are driving innovation. Artificial intelligence, including machine learning, may offer hope. Automation of design processes and cross-industry coordination have demonstrated that engineers are quite quick to adapt their capabilities to new, innovative systems [41, pp. 30-32].

The construction industry is cited as a major beneficiary of the integration of innovative IT systems, including artificial intelligence. It is predicted that by 2030, AI and machine learning will be present in all aspects of construction technologies. The main applications of AI in sustainable construction include the following areas [42, pp. 30-31]:

- designing energy-efficient buildings,
- building monitoring and management,
- optimization of the construction process,
- use of drones and robots.

The design of energy-efficient buildings is driven by the increasing pressure from developers and buyers to create buildings that consume as little primary energy as possible, meaning natural (not yet extracted), limited, and depleting energy. Reducing the heat transfer coefficient of heat-losing building envelopes increases the thickness of thermal insulation [43,

p. 1]. However, due to the physical phenomena occurring inside such buildings, the selection of insulating materials and their size becomes particularly difficult and requires numerous optimization analyses in terms of energy, thermal and humidity, and economics [44]. The use of AI in this area enables the analysis of large data sets containing information on climatic conditions, building materials, and structural parameters. This data can be used to create predictive models that aid in the development of building designs with optimal energy consumption (optimizing window layout, ventilation systems, and insulation).

After the investment is completed, artificial intelligence can support energy management and building maintenance. Monitoring systems analyze energy consumption, detect failures and irregularities, enabling preventive action. The use of AI in construction project management improves work coordination, predicts potential delays, and minimizes waste. Automation, including data analysis, aids logistics planning, which translates into reduced raw material and energy consumption [45, p. 82]. Robots and drones equipped with artificial intelligence can inspect hard-to-reach areas, which can increase work safety and efficiency and enable analysis of the technical condition of structures [46, p. 27].

In summary, the benefits of using AI in sustainable construction include: reduced energy and natural resource consumption, shorter project implementation times, improved structural quality and durability, increased work and user safety, and lower operating and maintenance costs. Despite its numerous benefits, implementing AI in construction faces numerous challenges, including the need for staff training, high initial investment costs, and data security issues. However, technological advancements and growing environmental awareness mean that the role of AI in sustainable construction will continue to grow.

3. CORRELATION OF SUSTAINABLE INNOVATIONS IN CONSTRUCTION WITH THE DEVELOPMENT OF ARTIFICIAL INTELLIGENCE

The contemporary construction sector faces challenges related to the need to increase efficiency, sustainable development, and reduce negative environmental impact. In this context, innovations that combine ecological, economic, and social aspects, striving to achieve sustainable development goals, are gaining increasing importance. One of the most important tools supporting this process is artificial intelligence, whose dynamic development is opening up new perspectives in the design, planning, and implementation of construction projects. This study will analyze the correlation between sustainable innovations in construction and the development of artificial intelligence, highlighting their interconnectedness and the potential to shape a more efficient, ecological, and intelligent construction sector.

3.1. Materials and methods

The presented research methodology presents the framework used in research on the relationship between sustainable innovation in construction and the development of artificial intelligence, focusing on appropriate research methods, tools, and techniques. Both the theoretical foundations of selected methods and their practical context will be discussed, allowing for an understanding of the research process itself and its impact on the final results.

The research subject can be an institution, an enterprise or a person [47, pp. 22-23], i.e. *the opinions of surveyed people selected for own research* . Similarly, the research subject is a phenomenon, objects or things about which research will be conducted or about which statements are formulated, referring to the assumed research problems [48, p. 38]. *The subject of the presented research will besustainable innovations in construction in the context of the development of artificial intelligence* .

The research objective pursued in the presented study, understood as: acquiring knowledge that is as accurate, reliable, simple, and general as possible, with optimal information content [47, p. 24], *consists in determining the dependencies of sustainable innovations in construction, such as generating sustainable building designs and automating construction tasks in sustainable construction, on the development of artificial intelligence. The research focused on identifying the impact of the following variables: education, gender, age, and personnel employed in the studied entities, on the indicated dependencies.*

To achieve the intended goal, research questions must be formulated to enable proper identification of the research subject. The questions should address a specific section of the research or a set of questions that will require detailed answers [49, pp. 42-43]. These can be simple questions that would determine a certain extent of ignorance or an activity defining the boundaries or purpose of the research [47, pp. 45-46]. Based on the presented concepts, the following *research problem was adopted:Can the demand for artificial intelligence in sustainable construction be influenced by variables such as education, gender or age of employees?*

3.2. Research procedure

The study area encompasses selected enterprises and their employees where artificial intelligence has been used to generate sustainable building designs and automate construction tasks. The total number of enterprises surveyed was 130, and the number of employees was 732. A representative sample of at least 100 for the surveyed companies and 330 for the surveyed employees, calculated using the following formula:

$$N_{min} = \frac{N}{1+\frac{4\cdot d^2 (N-1)}{Z^2}} = \frac{N}{1+\frac{0{,}0064\,(N-1)}{3{,}8416}}, \qquad (1)$$

Where:

N_{min} – minimum sample size,

N– population size (= 130 and 732),

Z – standard value for the significance level p ($Z = 1.96, for\ p = 0.05$)

d – assumed estimation error ($max – 4\% = >0.04$).

$$N_{minp} = \frac{130}{1+\frac{0,0064\,(130-1)}{3,8416}} = \frac{130}{1,2941} = 100; N_{minc} = \frac{732}{1+\frac{0,0064\,(732-1)}{3,8416}} = \frac{732}{2,2178} = 330$$

3.3. Methods, techniques and research tools and selected statistical methods

The relationships between variables were examined using 100 enterprises and 330 of their staff. Chi-square and Student's t-tests of independence were used to analyze the results. The main research tool was Excel software. The main research methods used were survey, statistical, and graphical. The significance level (α) was set at $\alpha = 0.05$ [50, p. 55].

The null hypothesis was defined as $H_0\colon E(n_{ij}) = E(\hat{n}_{ij})$, and the alternative hypothesis was defined as: $H_1\colon E(n_{ij}) \neq E(\hat{n}_{ij})$, where $\hat{n}_{ij}$ – theoretical numbers, while E is the expected value operator [51, p. 214].

Theoretical numbers were determined using the following formula [Greń, 1978, p. 131] :

$$\hat{n}_{ij} = \frac{n_{i.}n_{.j}}{n},(2)$$

where: $n_{i.}$, $n_{.j}$ – marginal numbers.

The statistics of the discussed test have the following form [Sobczyk, 2001, pp. 213-214] :

$$\chi^2 = \sum_{i=1}^{k}\sum_{j=1}^{r}\frac{(n_{ij}-\hat{n}_{ij})^2}{\hat{n}_{ij}}(3)$$

was used to test the significance of differences . In the case of homogeneous variances, the value of the statistic was calculated based on the following formula [52, p. 66]:

$$t = \frac{\bar{x}_1-\bar{x}_2}{\sqrt{\frac{n_1S_1^2+n_2S_2^2}{n_1+n_2-2}\cdot\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}}(4)$$

Where:

S_1^2, S_2^2 – sample variances,

$(\bar{x}_1 - \bar{x}_2)$ – difference in mean values, and in the denominator: standard error of this difference,

n_1, n_2 – sample sizes.

At $(n_1 + n_2 - 2)$degrees of freedom.

For non-homogeneous variances the test has the following form (52, p. 65):

$$t = \frac{\bar{x}_1-\bar{x}_2}{\sqrt{\frac{S_1^2}{n_1}+\frac{S_2^2}{n_2}}};\ \text{by}\left(\frac{1}{2}+\frac{S_1^2\cdot S_2^2}{S_1^2+S_2^2}\right)\cdot(n_1+n_2-2)(5)$$

In order to investigate the interdependence of quantitative features X and Y, the linear correlation coefficient was calculated according to the formula:

$$r(X,Y) = \frac{\sum_{t=1}^{n}(x_t-\bar{x})\cdot(y_t-\bar{y})}{\sqrt{\sum_{t=1}^{n}(x_t-\bar{x})^2\cdot\sum_{t=1}^{n}(y_t-\bar{y})^2}}(6)$$

Where:

n – feature values,

x_t and y_t = 1, 2, …, n,

$\bar{x}$i $\bar{y}$– arithmetic mean values of feature X and Y.

3.4. Generating sustainable building designs

Sustainable buildings are designed to minimize negative environmental impact, be energy-efficient, and ensure occupant comfort. Key features include efficient energy and water use, the use of renewable energy sources, the use of eco-friendly materials, and integration with the surrounding environment. The process of generating sustainable designs includes [53, p. 2]: preliminary analysis and requirements definition; site investigation and environmental analysis; concept and preliminary design; material and technology selection; energy optimization and renewable systems ; simulation and efficiency analysis; detailed design and documentation; implementation and supervision.

The preliminary analysis and requirements definition include defining the project's goals and sustainability requirements. Location, climatic conditions, resource availability, user needs, and applicable standards and certifications (LEED, BREEAM) must be considered. Both LEED and BREEAM certification apply to existing and newly constructed buildings. Obtaining the certification is divided into two parts: design documentation and the construction process. Furthermore, BREEAM certification can be applied to urban development projects [54, pp. 54-55].

The frequency distribution for the assessment of generating sustainable building designs depending on the education, gender and age of employees is presented in Table 1. The actual numbers are presented in Table 2 and the theoretical numbers in Table 3.

TABLE 1FREQUENCY DISTRIBUTION FOR THE ASSESSMENT OF GENERATING SUSTAINABLE BUILDING DESIGNS, BY EDUCATION, GENDER, AND AGE OF EMPLOYEES [OWN STUDY BASED ON OWN RESEARCH]

Generating sustainable building designs	Education				Sex				Age			
	Higher	%	The remaining	%	Woman	%	Man	%	Up to 40 years old	%	40+ years	%
Very high	21	21.8	33	14.2	20	14.7	33	17.2	40	19.4	16	12.5
High	33	33.9	60	25.6	19	13.9	37	19.4	49	23.8	23	18.3
Medium	22	22.4	52	22.2	31	22.8	52	26.3	51	25.2	26	20.6
Low	14	14.5	55	23.8	43	31.4	48	25.1	46	22.4	39	31.9
Very low	7	7.4	33	14.2	24	17.2	23	12	19	9.2	21	16.7
Total:	97	100	233	100	137	100	193	100	205	100	125	100
Number of positions:	330				330				330			

TABLE 2ACTUAL NUMBERS [OWN STUDY BASED ON TABLE 1]

Generating sustainable building designs	Education			Sex			Age		
	Higher	The remaining	Sum	Woman	Man	Sum	Up to 40 years old	40+ years	Sum
Very high	21	33	54	20	33	53	40	16	56
High	33	60	93	19	37	56	49	23	72
Medium	22	52	74	31	52	83	51	26	77
Low	14	55	69	43	48	91	46	39	85
Very low	7	33	40	24	23	47	19	21	40
Total:	97	233	330	137	193	330	205	125	330
Number of positions:	330			330			330		

TABLE 3THEORETICAL NUMBERS [OWN STUDY BASED ON TABLE 2]

Generating sustainable building designs	Education		Sex		Age	
	Higher	The remaining	Woman	Man	Up to 40 years old	40+ years
Very high	21	33	20	33	40	16
High	33	60	19	37	49	23
Medium	22	52	31	52	51	26
Low	14	55	43	48	46	39
Very low	7	33	24	23	19	21
Total:	97	233	137	193	205	125
Number of positions:	330		330		330	

Statistical relationships:

$\chi2 = 9.49$; significance $p = 0.0498 < 0.05$, hence the variables: “Generating sustainable building designs” and “Education” – show a statistically significant relationship.

$\chi2 = 5.23$; significance $p = 0.2643 > 0.05$, hence the variables: "Generating sustainable building designs" and "Gender" – do not show a statistically significant relationship.

$\chi2 = 9.64$; significance $p = 0.04693 < 0.05$, hence the variables: “Generating sustainable building designs” and “Age” – show a statistically significant relationship.

The demand for artificial intelligence in sustainable construction in terms of generating sustainable building designs depending on the education of employees is statistically significant ($p = 0.0498 < 0.05$) and was indicated most highly by people with higher education (55.7% – very high and high) – Figure 1.

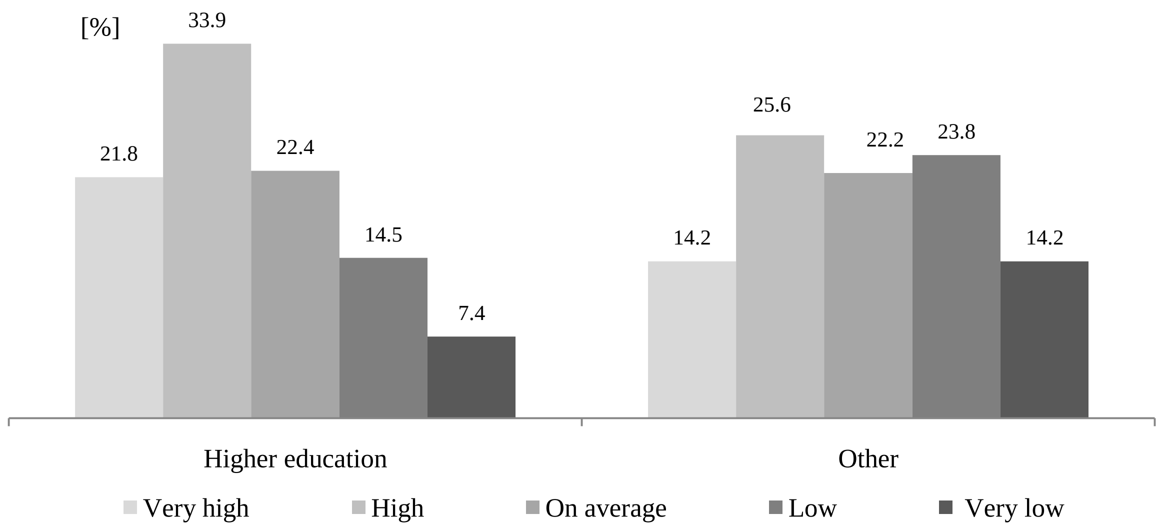

FIGURE 1. DEMAND FOR ARTIFICIAL INTELLIGENCE IN SUSTAINABLE CONSTRUCTION BASED ON THE GENERATION OF SUSTAINABLE BUILDING DESIGNS, DEPENDING ON EMPLOYEE EDUCATION [OWN STUDY, BASED ON TABLE 1]

The demand for artificial intelligence in sustainable construction according to the generation of sustainable building designs depending on the gender of employees is not statistically significant ($p = 0.2643 > 0.05$).

However, the need for artificial intelligence in sustainable construction according to the generation of sustainable building designs depending on the age of employees is statistically significant ($p = 0.04693 < 0.05$) and was indicated most highly by people under 40 years of age (very high and high: 43.2%) – Figure 2.

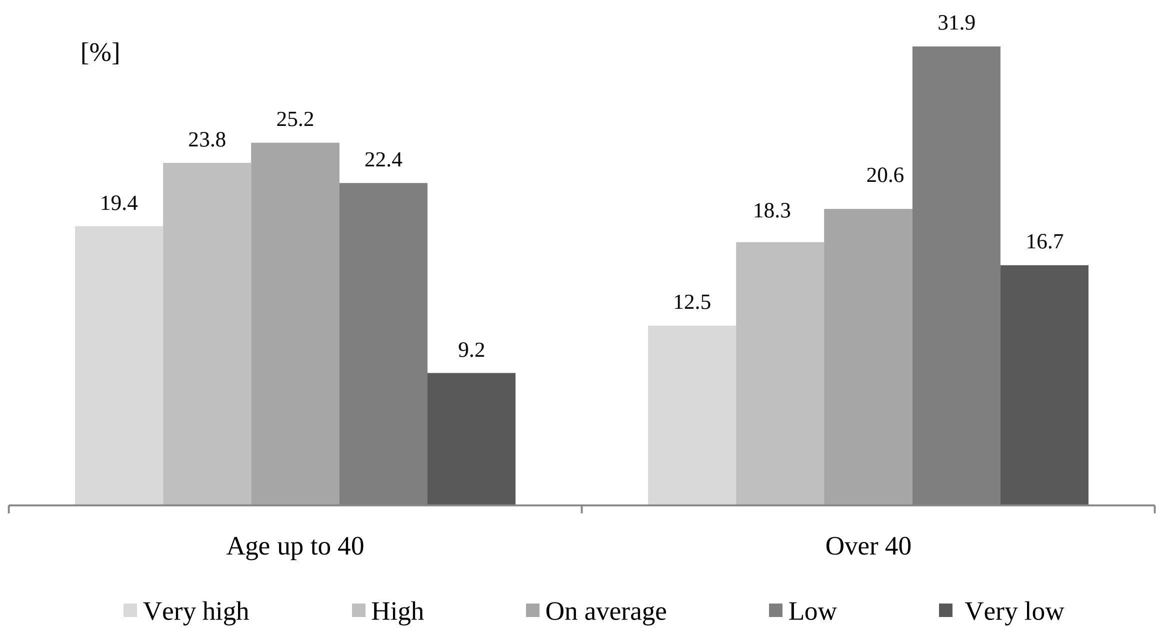

FIGURE 2. DEMAND FOR ARTIFICIAL INTELLIGENCE IN SUSTAINABLE CONSTRUCTION BASED ON THE GENERATION OF SUSTAINABLE BUILDING DESIGNS, DEPENDING ON THE AGE OF THE WORKERS
[OWN STUDY, BASED ON TABLE 1]

The most important benefits of designing sustainable buildings using artificial intelligence are:

- reduction of operating costs (lower energy and water consumption),
- increasing environmental protection (reducing pollutant emissions),
- improving the quality of life of users of sustainable buildings (better air quality, natural lighting, healthy building materials,
- increase in property value.

Generating sustainable building designs is a multi-stage process that requires an interdisciplinary approach and informed decisions at every stage. It's crucial to consider local conditions, utilize modern technologies, and strive to minimize negative environmental impact.

3.5. Automation of construction tasks in sustainable construction

In the context of the growing demand for sustainable solutions, automation of construction processes using AI is becoming an important tool for achieving goals related to efficiency, energy savings and minimizing environmental impact.

Automation of construction tasks in sustainable construction covers the following areas:

- automation of robots and machines: construction robots with AI can perform tasks such as bricklaying, painting, and tiling, minimizing material consumption,
- monitoring and supervision (analysis of data from sensors installed on the construction site, detection of irregularities, optimization of schedules, ensuring greater safety,
- resource and logistics management (AI algorithms optimize material deliveries).

The frequency distribution for the assessment of automation of construction tasks in sustainable construction depending on the education, gender and age of workers is presented in Table 4. The actual numbers are presented in Table 5 and the theoretical numbers in Table 6.

TABLE 4FREQUENCY DISTRIBUTION FOR THE ASSESSMENT OF CONSTRUCTION TASK AUTOMATION IN SUSTAINABLE CONSTRUCTION, BY EDUCATION, GENDER, AND AGE OF EMPLOYEES [OWN STUDY BASED ON OWN RESEARCH]

Automation of construction tasks in sustainable construction	Education				Sex				Age			
	Higher	%	The remaining	%	Woman	%	Man	%	Up to 40 years old	%	40+ years	%
Very high	22	21.6	29	12.4	20	14.7	38	19.5	46	22.3	15	11.8
High	28	29.2	51	21.7	19	13.9	40	21.2	50	24.6	24	19.2
Medium	24	25.1	62	26.6	31	22.8	47	24.1	47	22.7	27	21.5
Low	15	15.8	51	22.1	43	31.4	47	24.1	45	21.9	37	29.6
Very low	8	8.3	40	17.2	24	17.2	21	11.1	17	8.5	22	17.9
Total:	97	100	233	100	137	100	193	100	205	100	125	100
Number of positions:	330				330				330			

TABLE 5ACTUAL NUMBERS [OWN STUDY BASED ON TABLE 4]

Automation of construction tasks in sustainable construction	Education			Sex			Age		
	Higher	The remainin g	Sum	Woman	Man	Sum	Up to 40 years old	40+ years	Sum
Very high	22	29	51	20	38	58	46	15	61
High	28	51	79	19	40	59	50	24	74
Medium	24	62	86	31	47	78	47	27	74
Low	15	51	66	43	47	90	45	37	82
Very low	8	40	48	24	21	45	17	22	39
Total:	97	233	330	137	193	330	205	125	330
Number of positions:	330			330			330		

TABLE 6THEORETICAL NUMBERS [OWN STUDY BASED ON TABLE 5]

Automation of construction tasks in sustainable construction	Education		Sex		Age	
	Higher	The remaining	Woman	Man	Up to 40 years old	40+ years
Very high	15	36	24	34	38	23
High	23	56	24	35	46	28
Medium	26	60	33	45	46	28

Low	19	47	37	53	51	31
Very low	14	34	19	26	24	15
Total:	97	233	137	193	205	125
Number of positions:	330		330		330	

Statistical relationships :

$\chi 2 = 11.29$; significance $p = 0.0235 < 0.05$, hence the variables: "Automation of construction tasks in sustainable construction" and "Education" – show a statistically significant relationship.

$\chi 2 = 7.43$; significance $p = 0.1147 > 0.05$, hence the variables: "Automation of construction tasks in sustainable construction" and "Gender" – do not show a statistically significant relationship.

$\chi 2 = 13.09$; significance $p = 0.0108 < 0.05$, hence the variables: “Automation of construction tasks in sustainable construction” and “Age” – show a statistically significant relationship.
The demand for artificial intelligence in sustainable construction according to the automation of construction tasks in sustainable construction depending on the education of employees is statistically significant ($p = 0.0235 < 0.05$) and was indicated most highly by people with higher education (50.8% – very high and high) – Figure 3.

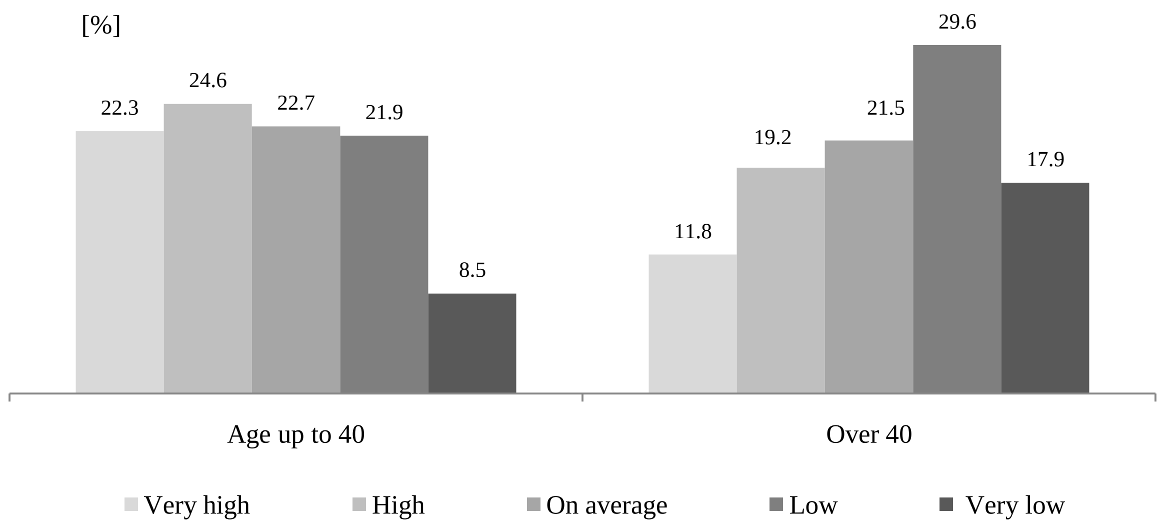

FIGURE 3. DEMAND FOR ARTIFICIAL INTELLIGENCE IN SUSTAINABLE CONSTRUCTION BASED ON AUTOMATION OF CONSTRUCTION TASKS IN SUSTAINABLE CONSTRUCTION, DEPENDING ON EMPLOYEE EDUCATION [OWN STUDY, BASED ON TABLE 4]

The demand for artificial intelligence in sustainable construction according to the automation of construction tasks in sustainable construction depending on the gender of employees is not statistically significant ($p = 0.1147 > 0.05$). However, the demand for artificial intelligence in sustainable construction according to the automation of construction tasks in sustainable construction depending on the age of employees is statistically significant ($p = 0.0108 < 0.05$) and was indicated most highly by people under 40 years of age (very high and high: 46.9%) – Figure 4.

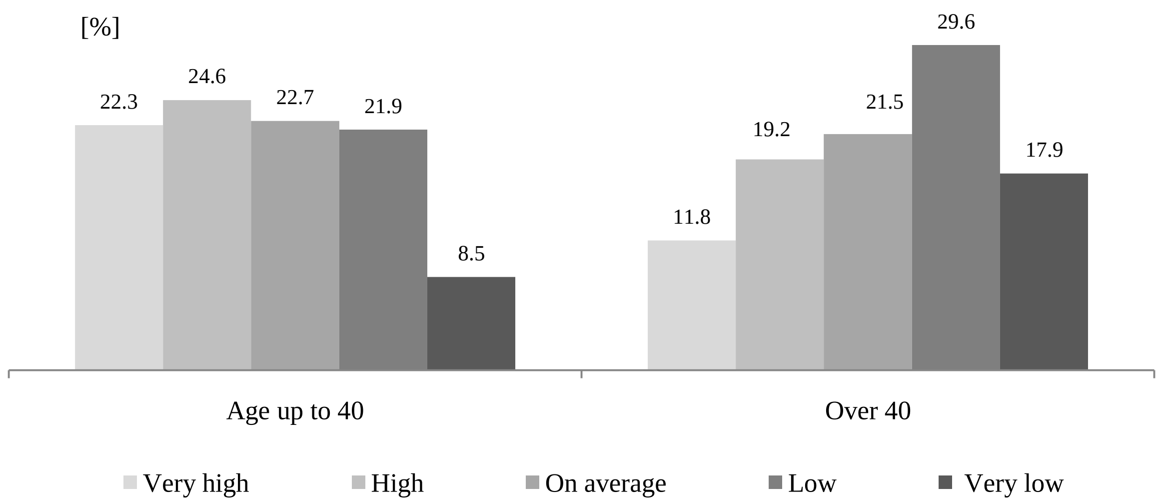

FIGURE 4. DEMAND FOR ARTIFICIAL INTELLIGENCE IN SUSTAINABLE CONSTRUCTION BASED ON THE AUTOMATION OF CONSTRUCTION TASKS IN SUSTAINABLE CONSTRUCTION, DEPENDING ON THE AGE OF THE WORKERS [OWN STUDY, BASED ON TABLE 4]

4. RESEARCH RESULTS

Empirical research identified relationships between employee education level, gender, and age and the demand for artificial intelligence in sustainable construction processes, particularly in generating sustainable building designs and automating construction tasks. Analysis of the results indicates that the variables of education and age have the strongest impact on the level of acceptance and use of AI. These relationships proved statistically significant in both design generation ($p = 0.0498 < 0.05$) and construction task automation ($p = 0.0235 < 0.05$). This indicates that individuals with higher education and younger workers (under 40 years of age) demonstrate greater openness and readiness to implement AI technologies in their daily professional practice.

The gender variable was not statistically significant in any of the analyzed cases, which may suggest that the degree of use of artificial intelligence in construction is not determined by demographic factors, but rather by technological competences and educational experience.

The data obtained confirm that AI is perceived as a tool supporting innovative processes in sustainable construction. The most frequently cited benefits included: reduced operating costs, increased energy efficiency, better use of raw materials, improved work environment quality, and increased safety on construction sites. In both the design and automation contexts, respondents recognize AI's potential in optimizing decision-making processes and improving the precision of design activities. This indicates growing environmental and technological awareness among construction professionals, as well as the industry's development direction toward digital transformation and intelligent resource management.

The research confirmed the hypothesis that sustainable innovations in construction are closely linked to the development of artificial intelligence, and the factor determining the pace of their adaptation is primarily the level of education and age of the engineering staff.

5. DISCUSSION

Contemporary challenges related to the need to reduce the negative impact of the construction sector on the environment necessitate the development of innovative solutions, including the use of artificial intelligence. As emphasized by S. Yin [55, p. 47], AI plays an important role in optimizing building design and construction processes, which contributes to reduced emissions and energy consumption. M. Kowalski [56, p. 112] emphasizes that artificial intelligence enables the automation of resource monitoring and management processes, which translates into more effective implementation of sustainable projects. The author notes that AI allows for the dynamic adaptation of construction strategies to changing environmental conditions.

Similarly, P. Nguyen and Y. Lee [57, p. 102] point out that integrating AI with Building Information Modeling technologies significantly improves energy planning and waste management during construction. The authors emphasize that artificial intelligence is an indispensable tool in striving for sustainable construction at the local and global levels.
P. Nowak [58, 130] analyzes the prospects for AI development in the sustainable construction sector, pointing to the need for further research and investment in this field. The author states that the demand for AI will grow with technological advancements and the growing environmental awareness of the industry. As evidenced by the cited publications, AI is playing an increasingly important role in promoting sustainable development in construction. Its application allows for process optimization, waste and emission reduction, and thus contributes to the achievement of sustainable development goals.

CONCLUSION

The development of artificial intelligence in the context of sustainable construction is a key element of contemporary technological transformation. Research findings indicate that implementing AI in design and construction processes allows for significant improvements in the energy, economic, and ecological efficiency of investments.

The use of machine learning algorithms, predictive systems, and intelligent analytical tools enables optimization of a building's lifecycle—from concept through implementation to operation. Sustainable innovations supported by artificial intelligence lead to a reduced carbon footprint, improved quality of space use, and rationalized resource consumption.

Empirical research findings highlight that the future of the construction industry will depend on the integration of digital skills among employees and on organizations' strategic approach to implementing new technologies. Artificial intelligence will become not only a supporting tool but also a factor redefining the way construction projects are planned, managed, and maintained.

The research objective, which involved determining the relationship between sustainable innovations in construction, such as generating sustainable building designs and automating construction tasks in sustainable construction, and the development of artificial intelligence—as expressed by survey participants, with their education, gender, and age as variables—showed that people under 40 with a university degree have a significant impact on AI development. Continued research in similar areas may identify other factors influencing the development of sustainable construction using artificial intelligence.

In the long term, AI can be expected to become an integral element of a sustainable innovation ecosystem, enabling the development of intelligent, efficient, and environmentally responsible construction. However, the success of this process will depend on maintaining a balance between technological progress and ethical and social aspects, which poses a challenge for future policies and strategies for the industry's development.

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