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Research paper

Risk analysis in the environmental impact assessment of building construction innovations

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Abstract: Buildings in Poland are still constructed using technologies and methods created decades ago, even though many new technologies can be applied. Such an approach in the construction process is not sufficient to ensure the sustainable development of the world. Therefore, there is a great need for implementing new, innovative technical, economic, and social solutions. Innovation can be considered as any change that is beneficial for the entity that introduces it. The challenges that the construction sector faces nowadays are mostly related to the concept of sustainable development. The main trends in innovations are the shift towards more resource- and energy-efficient ways of construction as well as implementing the principles of the circular economy. In this article, we present innovative technologies applied in the construction sector that meet the requirements of sustainable development. Also, we propose a method for assessing the environmental impact of innovative technologies currently used in the construction sector. As the proposed methods are primarily based on expert knowledge, it was necessary to determine the risk of making a wrong decision to apply innovative technology in practice based on an assessment made by a person with appropriate competencies.

Keywords: BMS, construction innovations, environment, fuzzy numbers, triangle membership function

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1. Introduction

Nowadays, most buildings in Poland are constructed using technologies and methods that were elaborated several decades ago (brick technologies: ceramic, aerated concrete, silicate, reinforced concrete, and steel) [1,2]. Unfortunately, these methods make it impossible to ensure the sustainable development of the world today. To change this, it is necessary to implement new, innovative technical, economic, and social solutions.

Innovation is considered any change that is beneficial for the entity that introduces it [3]. The modern construction sector is mostly facing challenges related to the concept of sustainable development. One of the main trends in building innovation is the shift towards a more resource, and energy-efficient way of constructing, operating, and implementing the principles of the circular economy [1,2,4].

In the literature, we can find characteristics of risk assessment methods elaborated by a group of experts and methods for assessing the environmental impact of a construction project [3], [5–9]. However, so far, the environmental impact assessment and the risk assessment of applying innovations have been performed separately.

So far, however, separate assessments of the impact on the natural environment and the risk assessment of applying innovations have been made [9–15]. However, there is no method for estimating the level of risk of incorrect assessment of the environmental impact of the application of specific construction innovation. Moreover, there is no method for estimating the risk of incorrect assessment of the environmental impact of applying a particular construction innovation.

In this paper, we present selected innovative technologies used in the construction sector that meet sustainable development criteria. In addition, an original expert method for assessing the environmental impact of building innovations has been proposed. This method links environmental impact assessment and the risk of incorrect evaluation during the evaluation process. By applying the proposed methodology (RIM – Risk Innovation Methodology), decision-makers obtain a quick method of the initial selection of innovations and a way of assessing the risk of making a wrong decision. The application of the proposed method in the construction sector will help to increase the level of innovation in the mentioned sector.

The scope of the paper includes justification for undertaking the research, description of the criteria applied for environmental impact assessment, characteristics of the evaluation method (in real and fuzzy numbers), description of the method applied for estimating the risk of making a wrong decision based on the expert assessment, examples of the application of the innovation assessment method and the method of risk assessment, and finally conclusions from the conducted research.

2. Assessing of construction environment

Investors, designers, and construction contractors have an enormous choice of new technologies as well as technical and material solutions developed by manufacturers of materials and research centers [16, 17]. Suppliers of new technologies claim that their products are innovative, ecological, and match the concept of sustainable development of the world [18–20].

Unfortunately, some research indicates that the degree of uncertainty when introducing it in the construction sector is particularly high [21]. No wonder then that methods of assessing innovation in the construction sector have been developed for almost thirty years. For example, Coccia [22] presents an approach that attempts to measure the impact of innovation on the geoeconomic environment, distinguishing between positive and negative aspects, to disseminate further eco-innovations that are important for future sustainable development and a modern economy. From the technological point of view, innovation is considered a revolution comparing the current situation. On the other hand, Nazarko [23] states that technology assessment is regarded as a unique form of forward-looking analysis, i.e., assessing the impact that introduced or developed innovations may have on society, the environment, and the economy. In this paper, innovation methods described in the literature [21,24,25] were assessed in terms of minimizing energy consumption, ease of use of technology, dependence on local problems, adaptability, ease of configuration, and ease of disassembly. Life cycle aspects, growing user awareness, and the market potential of specific innovations were also considered.

Literature review shows that a consistent method for assessing the environmental impact of a specific technical solution in the construction sector, dedicated to innovative technology, has not yet been developed. At the same time, the development of the construction industry in today's world is unimaginable without digitization, automation, and the use of new technologies. The problem of decision-making regarding the use of a specific innovation in the conditions of market competition of construction companies becomes of key importance. Decision-makers in the construction process look for simple methods to evaluate innovation. Many investors, in turn, pay attention to environmental aspects and try to minimize the negative impact on the environment of the constructed buildings. Existing environmental impact assessment systems for buildings and structures, such as LEED or BREEM [1], do not promote innovation. Therefore, there is a need for a method to assess the environmental impact of innovation in the construction sector. Taking the above into account, then we try to develop and test such a methodology.

According to statistics, the broadly understood construction sector consumes 40% of primary energy, emits 35% of greenhouse gases, and produces 20% of industrial waste [2]. In addition to mineral and organic resources, the construction sector is also a large consumer of water throughout the building cycle. Taking into account the above facts and a significant level of innovation in terms of reducing energy consumption, reducing air pollutant emissions as well as managing and reducing water consumption, the following criteria for assessing the impact of the building structure on the environment were adopted:

- minimum accumulated primary energy,
- minimal carbon footprint,
- minimal waste that cannot be effectively processed later,
- minimum water consumption throughout the building's life cycle.

3. Assessment criteria

The life-cycle assessment (LCA) analysis is commonly used for assessing the environmental impact throughout the entire life cycle. The concept of this method was created in the 1960s. LCA analysis aims to determine the mutual impact of the considered process and the environment and quantifying the mass and energy streams transmitted and taken from the environment. The following processes are considered [4]:

– mining, and processing of natural resources needed to manufacture a given product,
– production process,
– distribution,
– consumption, and possibly reprocessing,
– storage after the product has been abandoned.

At each of these stages, impacts are generated that may have both negative and positive effects on the environment. The total environmental impact is determined based on a balance of negative and positive impacts.

In the case of buildings and engineering structures, the LCA method can be considered an analysis of the impact of individual building materials on the environment. According to the concept, the analysis should take into account the production process of particular materials. Engineering facilities can perform very different functions, have a long lifetime, and significantly interfere with the surrounding environment.

As for newly constructed objects, determining the condition of buildings after the end of the operation is a problematic issue. However, in old buildings, it isn't easy to find data regarding their construction. To perform the analysis, it is necessary to set the limits of the considered system, which strictly depend on its function.

For buildings and engineering structures, the following stages should be considered: construction (design and preparation), exploitation (use, repairs), termination of use (demolition, change of purpose).

The LCA method is an interdisciplinary tool for the comprehensive determination of environmental impact. When analyzing the technical life cycle of construction products, the factor determining the length of service life is durability. The higher the longevity – the lower the threat to the natural environment due to the collection of natural raw materials, as well as energy and water for the production of construction products and the construction of a new facility, not counting the problems with the utilization of waste remaining after the demolition of a technically degraded building.

Taking into account the mentioned above characteristics of the LCA method, it was decided to compare innovative technologies in the construction sector by quantifying qualitative estimation made by experts regarding minimum accumulated primary energy, minimum carbon footprint, minimum waste that cannot be processed efficiently afterward, minimum water consumption over the building's life cycle.

Cumulated primary energy

Cumulated primary energy is the total energy consumption considering all manufacturing and transport processes, from obtaining raw materials to the final process leading to producing a given product. Cumulated energy consumption applies not only to materials and products but also to primary fuels and direct energy carriers.

Carbon footprint

A carbon footprint is the total set of greenhouse gases emitted by an organization or a person during a product's life cycle. Another definition used in the literature is a measure of the total amount of carbon dioxide (CO_2) and methane (CH_4) emitted, including nitrous oxide (N_2O). The emission of these substances is estimated for a specific population, system, or activity regarding all relevant sources in a given area in a specific time-space.

The analysis of carbon dioxide emissions into the atmosphere takes into account all energy-consuming processes. The value of the initial cumulative CO_2 emission to the atmosphere is the sum of [4]: carbon dioxide emissions produced during material production, carbon dioxide emissions generated during transport of materials to the construction site, carbon dioxide emissions during the facility's construction.

Significant discrepancies can be found when determining cumulative energy and cumulative CO_2 emission for wood. Cumulated energy varies between 0.511 and 10.412 [MJ/kg]. In the case of CO_2 emission, the wood's absorption of carbon dioxide during its lifetime should be considered.

Waste

The construction sector is a branch of the highly material-intensive economy. New construction and renovation of existing buildings require significant consumption of raw materials and construction products. At the same time, we deal with construction waste in both cases, although the scale of this phenomenon when renovating facilities, in particular, total demolitions, is larger. Since waste is generated at various construction stages, the possibilities of preventing its formation are strictly related to the applied technology.

When commencing construction works, the following principles should be considered: optimization of the consumption of building materials, the use of modern devices and machines characterized by so-called non-waste or low-waste technology, compliance with technological process parameters, analyzing and verifying applied technologies and material consumption standards in terms of reducing waste.

The criterion of LCA assessment for a given house construction technology is waste management because according to the European Union guidelines, in 2020, as much as 70% of the construction waste should be recycled,

– analyzes of the American association Building Materials Reuse Association indicates that up to 85% of materials used for building construction can be used again,
– during the construction of new facilities and renovations of existing ones, diverse forms of waste are generated – debris, scrap, metal, glass, structural elements, etc., which should be re-used following the concept of sustainable development,
– from the construction of the facility, through renovation, reconstruction, to demolition, it is possible to recover raw materials and construction products at all stages.

Effective construction waste management is part of the rational use of resources in the construction sector and the mitigation of the negative impact of the construction process on the environment. Therefore, within the whole life cycle of a building, waste management should be taken into account.

Water consumption

Optimization of water consumption, reduction of energy demand for hot utility water, and reducing the amount of sewage produced are some of the critical aspects of sustainable construction. Actions related to the reduction of water consumption (and in parallel, the amount of wastewater discharged into the sewage system) concern the reduction of tap water consumption and the use of gray water.

Greywater is constituted by wastewater input from baths and showers, washing machines, dishwashers, and kitchen sinks, except for water from toilets [26]. This kind of water may be easily re-used in the water cycle of any building after prior purification. The requirements regarding water quality are country-specific, but usually, they are based on the criteria considering organic, solids, and microbiological contents.

4. Evaluation of the criteria

Many environmental impact assessment methods have been developed [16], but only a few can be used to evaluate innovative solutions. Therefore, an original, dedicated method (RIM) of assessing the impact of construction innovations on the environment (RIM) was developed [28]. For each of the four adopted criteria, two assessment scales are proposed for quantitative analysis and comparison of the analyzed innovations. The first scale is described in integers between –2 and 2, and the second one in fuzzy numbers with a triangular membership function.

The integer rating is given according to the following scale of the impact on the environment:

- rating "–2" – negative impact,
- rating "–1" – slight negative impact,
- rating "0" – neutral impact,
- rating "1" – slight positive impact,
- rating "2" – positive impact.

The rating in fuzzy numbers with a triangular membership function is given according to the following scale of the impact on the environment:

- rating "triangle (x, –2, –2, –1)" – negative impact,
- rating "triangle (x, –2, –1, 0)" – slight negative impact,
- rating "triangle (x, –1, 0, 1)" – neutral impact,
- rating "triangle (x, 0, 1, 2)" – slight positive impact,
- rating "triangle (x, 1, 2, 2)" – positive impact.

The evaluation of innovations is always carried out concerning the most popular solution (design methods, construction technology, or building material).

The adopted scale of grades in integers from –2 to 2 reflects the environmental impact of a given innovative solution. Most researchers creating assessment methods for a given solution assume a value of "0" as a neutral environmental impact or impact the same as the reference solution. In the literature [5, 6] various grading scales can be found, e.g. symmetrical (–1, –0.5, 0, 0.5 ,1) or asymmetrical scales (–2, –1.0, 1, 2, 3, 4, 5) used in the GBC 98 system. A symmetrical integer scale was chosen because it allows for equal strength of positive and negative impact assessment (symmetry) and simple transformation into fuzzy numbers.

On the assessment scale in fuzzy triangular numbers, it is possible to show the level of uncertainty (risk) of expert assessments and assign linguistic values such as positive impact to this assessment. Therefore, this scale was used as an alternative to integer evaluation. The total assessment of a given innovative technology is the sum of partial expert assessments for the four assessment criteria (cumulated primary energy, carbon footprint, waste, water consumption).

The final rating in the integer scale is the sum of the rating values (–2, –1, 0, 1, or 2) assigned to the evaluated innovation. As for the fuzzy number scale, the final rating is also the sum of the environmental impact values assigned to the innovation.

5. Risk of making incorrect decision

It was assumed that the application of a specific innovation would have a positive impact on the environment concerning the currently existing solution if the value of the total assessment in integer numbers from all criteria is positive, i.e., it belongs to the set $\{1, 2, 3, 4, 5, 6, 7, 8\}$.

To assess the risk of the incorrect final evaluation, it was decided to use the final summary evaluation in fuzzy triangular numbers. For this number, the concept of "Spread" is defined as the difference between "$a3$" and "$a1$" in a triangular fuzzy number (x, $a1$, $a2$, $a3$,):

$$\text{Spread} = a3 - a1. \tag{5.1}$$

In the case of evaluation by one expert, the risk of incorrect final evaluation will be exactly equal to the spread.

It was assumed that the value: 4 – corresponds to a very low risk, 5 – corresponds to negligible risk, 6 – corresponds to medium risk, 7 – corresponds to high risk, 8 – corresponds to very high risk. The risk assessment scale takes values from 4 to 8 because the final score is the sum of four partial scores.

If several experts are assessed, the risk will be evaluated based on the mean rounded to natural numbers from the spreads determined based on the total fuzzy score.

Additionally, as a measure of risk in the case of an assessment by several experts, the probability value of accepting a negative total assessment value P(x) was adopted.

6. Analysis of the environmental impact assessment

6.1. Assessment methodology

The environmental impact assessment of building innovations was carried out by 11 specialists in the field of the sustainable construction (SC) sector and 2 specialists regarding building construction (BC). All of them had the professional title of engineer. In addition, the assessment was performed by 5 experts with a Ph.D. title:

- Expert 1 – civil engineer, an expert in the sustainable development construction sector,
- Expert 2 – civil engineer and architect, an expert in the sustainable development construction sector,
- Expert 3 – architect, an expert in the field of life cycle assessment (LCA) in the construction sector
- Expert 4 – environmental engineer, an expert in the field of water supply and management,
- Expert 5 – environmental engineer, an expert in the field of the energy sector and environment. Specialist regarding installations in smart buildings.

Specialists and experts carried out environmental impact assessments of four different innovative building solutions. All specialists and two experts (experts 3 & 4) were previously participating in detailed lectures regarding innovative solutions in the construction sector. However, it must be noted that the impact of the lectures on the evaluation of innovations will be then investigated. Currently, the sample of people who did not listen to the lectures and assessed the impact of innovations on the environment is too small to draw any credible conclusions. The other experts made their assessment based only on their knowledge. Experts are people with at least a Ph.D. in engineering and 5 years of professional experience in a given field. They are all lecturers at the Warsaw University of Technology. The age of experts varies from 30 to 58 years. Specialists are young people (under 30 years), but with at least the professional title of a construction engineer, working for a short time in construction companies and deepening their knowledge during master's studies. Expert 5 is a habilitated Ph.D. specializing in smart installations. As he has no typical construction experience and did not attend the lectures, he was only assessed innovations in the field he specializes in.

Examples of the application of the innovation assessment method and its risk assessment were selected to analyze the main phases in the life cycle of the building, i.e.:

- design phase – technology for erecting buildings (in particular, a comparison of structural buildings materials) and an assessment of the basic installations with which each facility is equipped, i.e., water supply,
- construction phase – advanced automation, i.e., the use of robots,
- use phase – advanced building and energy management system.

Moreover, examples of innovation assessment were selected in terms of different levels of difficulty in assessing individual criteria of the innovation impact on the environment by experts. This selection of examples was made to show the various aspects of the proposed evaluation of innovations by experts and, above all, the different values of the risk assessment of misjudging the environmental impact of innovations.

In the following chapters, the results from performed assessments are presented along with the risk analysis of a decision-maker making an incorrect decision based on expert evaluation.

6.2. Environmental impact assessment of wall construction using rammed earth technology

Characteristic of innovation

The rammed earth technology [27, 28] consists of dynamic compaction of the moist soil mixture in layers in the formwork set on a stable foundation. The primary component of the mixture is inorganic soil, usually obtained directly from the construction site. The factor limiting the usefulness of the soil in the rammed earth technology is the amount of organic substances as well as the content and mineral composition of the clay fraction. To increase the mechanical strength and durability, stabilizers are added to the soil mixture, usually a few percent addition of Portland cement. Moisture is a key factor in the process of whipping the mix. The layers of the loose mix are placed in the formwork and compacted (the height of the layer is usually approx. 15 cm). The formwork is then removed.

Assessment of the impact of innovation on the environment

The evaluators were asked to carry out an environmental impact assessment of the wall made in the rammed earth technology by comparing the expected change of the above-described four parameters (cumulative energy, cumulative CO_2 emission, waste generation, and water consumption) compared to the parameters of a wall made of solid ceramic brick. It was assumed that the operational parameters of the partition in both technologies are the same.

The results of the assessment (described above by the method) of the environmental impact of the rammed earth wall are shown in Table 1.

Table 1. Environmental impact assessment of the rammed earth wall (SC – sustainable construction, BC – building construction)

No.	Evaluator	Energy	CO_2	Water	Waste	Evaluation		
						Final	Fuzzy	Spread
1	Specialist SC	2	2	2	2	8	$(x, 4, 8, 8)$	4
2	Specialist SC	2	2	1	2	7	$(x, 3, 7, 8)$	5
3	Specialist SC	2	2	1	2	7	$(x, 3, 7, 8)$	5
4	Specialist SC	2	2	1	2	7	$(x, 3, 7, 8)$	5
5	Specialist SC	2	2	2	2	8	$(x, 4, 8, 8)$	4
6	Specialist SC	2	2	1	2	7	$(x, 3, 7, 8)$	5
7	Specialist SC	2	2	1	2	7	$(x, 3, 7, 8)$	5
8	Specialist SC	2	2	1	2	7	$(x, 3, 7, 8)$	5
9	Specialist SC	2	2	2	2	8	$(x, 4, 8, 8)$	4
10	Specialist SC	2	2	2	2	8	$(x, 4, 8, 8)$	4
11	Specialist BC	2	2	2	2	8	$(x, 4, 8, 8)$	4
12	Specialist SC	2	2	1	0	5	$(x, 1, 5, 7)$	6
13	Expert I	2	2	2	2	8	$(x, 4, 8, 8)$	4
14	Expert II	1	1	1	1	4	$(x, 0, 4, 8)$	8
15	Expert III	2	2	1	2	7	$(x, 3, 7, 8)$	5
16	Expert IV	2	2	2	2	8	$(x, 4, 8, 8)$	4
	Mean	1.94	1.94	1.44	1.81	7.13		4.81
	Mean (rounded)	2	2	1	2	7		5

One of the evaluators carried out detailed studies of the rammed earth technology, considering parameters having an environmental impact such as the energy required to produce 1 m^3 of rammed earth (CSEB), CO_2 emissions from this process, water consumption, and waste production. A comparison of the values of the first two parameters (energy and CO_2 with the corresponding values for a brick wall or concrete block is shown in Fig. 1.

When analyzing Fig. 1, we can conclude that much lower energy consumption and CO_2 emission are observed when using rammed earth technology instead of the traditional brick wall.

According to an expert who studies the technology of rammed earth when water is used, its consumption depends on the humidity of the locally sourced raw material and is always

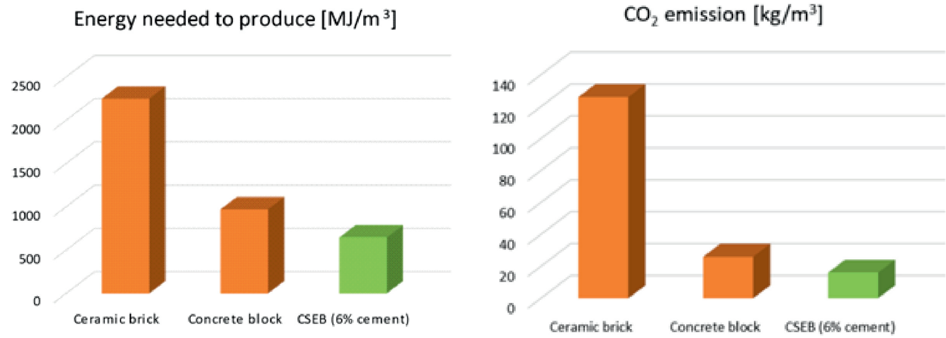

Fig. 1. Comparison of energy required to produce 1 m^3 of rammed earth and its associated CO_2 emission to the brick wall and concrete block

less than the water consumption of masonry wall technology. Waste is virtually non-existable or a minimum percentage of tiered earth technology. Also, after the lifetime of the building, demolition land can be used as a full-fledged raw material for the construction of another building from the ground or as environmentally harmless waste.

Recommendation for the decision-maker

The values of the parameter "Mean (rounded)" indicate for the three criteria the maximum assessment (value = 2) and the fourth criterion, an assessment indicating a slight positive (value = 1) of the environmental performance of smart building technologies. The total average rounded rating in integer numbers is 7. Therefore, the recommendation to the decision-maker is unequivocal and indicates a positive impact on the environment of the decision to use rammed earth technology instead of a masonry wall made of full bricks.

Risk assessment

The mean value rounded to natural numbers for "spread " is equal to 5. Which means a small risk of incorrect assessment of the final assessment. Probability of taking a negative total evaluation value $P(x) = 0$.

6.3. Environmental impact assessment of rainwater recovery technology with water purification module

Characteristic of innovation

According to Fangrat et al. [29], rainwater recovery technology with a water purification module allows managing rainwater from available roof surfaces. Only drain water from the roof should be used, as it contains a relatively small amount of pollution. Rainwater from the roof through the system of gutters and drain pipes is brought into the tanker. In the tanker, water is initially filtered. The underwater pressure pump transports water from the tanker through a 3-stage filter and UV disinfection system to the receivers in the building. Purified rainwater flows through the filter system initially through 2 precipitate filter cartridges (first 20 μm and then 10 μm), then through the active carbon filter cartridge, and finally by UV disinfection.

Sediment filter and activated carbon filter cartridges should be replaced every 4 months, and the UV disinfection lamp has an expected lifetime of 10 000 hours. The installation is powered by electricity (230 V/50 Hz) from a distribution network or photovoltaic installation.

Assessment of the impact of innovation on the environment

The evaluators were asked to carry out an environmental impact assessment of the technology by comparing the expected change of the above-described four parameters (cumulative energy, cumulative CO_2 emission, waste generation, and water consumption) compared to the extraction of drinking water from the water supply network.

The results of the environmental impact assessment of rainwater recovery technology with water purification module are presented in Table 2.

Table 2. Environmental impact assessment of rainwater recovery technology with water purification module (SC – sustainable construction, BC – building construction)

No.	Evaluator	Energy	CO_2	Water	Waste	Evaluation		
						Final	Fuzzy	Spread
1	Specialist SC	–1	0	2	2	3	$(x, -1, 3, 5)$	6
2	Specialist SC	0	0	2	–1	1	$(x, -3, 1, 5)$	8
3	Specialist SC	0	2	2	1	5	$(x, 1, 5, 7)$	6
4	Specialist SC	2	2	2	0	7	$(x, 2, 6, 7)$	5
5	Specialist SC	0	1	2	0	3	$(x, -1, 3, 6)$	7
6	Specialist SC	–1	2	2	1	4	$(x, 0, 4, 6)$	6
7	Specialist SC	–1	0	2	–1	0	$(x, -4, -0, 3)$	6
8	Specialist SC	0	0	2	0	2	$(x, -2, 2, 5)$	7
9	Specialist BC	0	1	2	2	5	$(x, 1, 5, 7)$	6
10	Specialist SC	–1	–1	2	1	1	$(x, -3, 1, 4)$	7
11	Expert I	1	1	2	1	5	$(x, 1, 5, 8)$	6
12	Expert II	–2	–2	1	–1	–4	$(x, -6, -4, -1)$	7
13	Expert III	–1	–1	2	–1	–1	$(x, -5, -1, 2)$	7
14	Expert IV	1	1	2	0	4	$(x, 0, 4, 7)$	7
	Mean	–0.21	0.43	1.93	0.29	2.50		6.50
	Mean (rounded)	0	0	2	0	3		7

Recommendation for the decision-maker

The values of the parameter "Mean (rounded)" indicate, neutral evaluation for three criteria (value = 0), and in the case of the fourth criterion, an assessment indicating the positive (value = 2) of the rainwater recovery technology with the environmental water purification module. The total mean (rounded) rating in integer numbers is 3. Regarding the adopted criteria, the recommendation to the decision-maker is somewhat positive and indicates a slightly positive environmental impact when deciding to use rainwater recovery technology with a water purification module.

Risk assessment

The mean value rounded to natural numbers for "spread" is equal to 7. Probability of taking a negative total evaluation value $P(x) = 0.14$.

6.4. Environmental impact assessment of advanced automation – the use of robots

Characteristic of innovation

The robots are currently widely used in the construction sector for surveying works, prefabrication plants, welding, finishing works, and erecting structures. The subject of the innovation assessment was the use of robots to construct a solid brick wall. The robot worked alongside construction workers but placed three times as many bricks as humans. Another advantage of using the robot was arranging bricks in unconventional patterns to obtain new structures. The robot performed the tasks precisely and did not destroy the material. Such automation significantly increases the level of work efficiency and reduces the amount of waste [18, 20].

Assessment of the impact of innovation on the environment

The results of the assessment of the environmental impact of the use of robots in the construction sector are presented in Table 3.

Table 3. Environmental impact assessment of the use of robots (SC – sustainable construction, BC – building construction)

No.	Evaluator	Energy	CO_2	Water	Waste	Evaluation		
						Final	Fuzzy	Spread
1	Specialist SC	2	1	1	2	6	$(x, 2, 6, 8)$	6
2	Specialist SC	1	1	0	2	4	$(x, 0, 4, 7)$	7
3	Specialist SC	0	0	0	2	2	$(x, -3, 0, 3)$	6
4	Specialist SC	–2	–1	1	2	0	$(x, -2, 2, 5)$	6
5	Specialist SC	–1	–1	0	1	–1	$(x, -5, -1, 3)$	8
6	Specialist SC	–2	–1	1	2	0	$(x, -3, 0, 3)$	6
7	Specialist SC	2	2	1	2	7	$(x, 4, 7, 8)$	4
8	Specialist SC	–1	–1	0	–1	–3	$(x, -7, -3, 1)$	8
9	Specialist SC	2	2	1	1	6	$(x, 2, 6, 8)$	6
10	Specialist BC	0	–1	1	2	2	$(x, -2, 2, 5)$	7
11	Specialist SC	2	2	0	1	5	$(x, 1, 5, 7)$	6
12	Specialist BC	0	0	1	0	1	$(x, -3, 1, 5)$	8
13	Specialist SC	–1	–1	0	1	–1	$(x, -5, -1, 3)$	8
14	Expert I	2	1	2	2	7	$(x, 3, 7, 8)$	5
15	Expert II	–1	–1	0	0	–2	$(x, -6, -2, 2)$	8
16	Expert III	1	1	0	2	4	$(x, 0, 4, 7)$	7
17	Expert IV	1	1	1	1	4	$(x, 0, 4, 8)$	8
	Mean	0.29	0.24	0.59	1.29	2.41		6.71
	Mean (rounded)	0	0	0	1	2		7

Recommendation for the decision-maker

The values of the parameter "Mean (rounded)" indicate for the three criteria a neutral evaluation (value = 0), and for the fourth criterion, the evaluation indicates a slightly positive (value = 1) environmental impact of the investigated intelligent building technology. The total mean rounded score in integer numbers is 2. Given the adopted criteria, the recommendation for the decision-maker is rather positive and indicates a slightly positive environmental impact of using robots in the construction industry to build walls.

Risk assessment

The mean value rounded to natural numbers for "spread" is equal to 7. Probability of taking a negative total evaluation value $P(x) = 0.14$. That means a high risk of incorrect final evaluation.

6.5. Environmental impact assessment of smart buidlings

Characteristic of innovation

According to Kaliszuk-Wietecka et al. [12], a smart building is a term for a technically highly advanced facility with sensors and detectors and a single, integrated management system for all installations in the building. Thanks to information coming from various system elements, the building can react to changes in the environment inside and outside, which leads to maximization of functionality, comfort, and safety, minimization of operating and modernization costs, and reduction of harmful pollutants emissions. The smart building system should not negatively affect the people in its environment. It is estimated that smart building technology brings up to 30% energy savings in the use phase of the building and correspondingly lowers CO_2 emissions.

Assessment of the impact of innovation on the environment

The results of the assessment of the environmental impact of smart buildings in the construction sector are presented in Table 4.

In this case, also an expert in the field of energy and environment, specializing in smart buildings systems was included – Expert V. He has been taught in terms of the methodology used for assessing the environmental impact of innovation.

Recommendation for the decision-maker

The values of the parameter "Mean (rounded) indicate for the three criteria the maximum ratings (value = 2), and for the fourth criterion, the ratings showing a slightly positive (value = 1) environmental impact of smart building technologies. The total mean rounded score in integer numbers is 5. Therefore, the recommendation for the decision-maker is rather unambiguous and indicates the positive environmental impact of the decision to use smart building technologies.

Risk assessment

The mean value rounded to natural numbers for "spread" is equal to 5. Probability of taking a negative total evaluation value $P(x) = 0.06$. That means a low risk of incorrect final evaluation.

Table 4. Environmental impact assessment of smart buildings (SC – sustainable construction, BC – building construction)

No.	Evaluator	Energy	CO_2	Water	Waste	Evaluation		
						Final	Fuzzy	Spread
1	Specialist SC	2	2	2	2	8	$(x, 4, 4, 8)$	4
2	Specialist SC	2	2	2	1	7	$(x, 3, 7, 8)$	5
3	Specialist SC	2	2	2	0	6	$(x, 2, 6, 7)$	8
4	Specialist SC	1	1	1	0	3	$(x, -1, 3, 7)$	8
5	Specialist SC	–2	2	2	2	4	$(x, 1, 4, 5)$	4
6	Specialist SC	2	2	2	1	7	$(x, 3, 7, 8)$	5
7	Specialist SC	2	2	2	2	8	$(x, 4, 8, 8)$	4
8	Specialist SC	2	1	2	2	7	$(x, 3, 7, 8)$	5
9	Specialist SC	2	2	2	2	8	$(x, 4, 8, 8)$	4
10	Specialist BC	1	1	0	–1	1	$(x, -3, 1, 5)$	8
11	Specialist SC	2	2	1	–2	3	$(x, 1, 3, 5)$	4
12	Specialist BC	2	2	0	0	4	$(x, 0, 4, 6)$	6
13	Specialist SC	2	2	2	1	7	$(x, 3, 7, 8)$	5
14	Expert I	2	2	2	2	8	$(x, 4, 8, 8)$	4
15	Expert II	–1	–1	0	0	–2	$(x, -6, -2, 2)$	8
16	Expert III	2	2	2	0	6	$(x, 2, 6, 7)$	5
17	Expert IV	2	2	2	1	7	$(x, 3, 7, 8)$	5
18	Expert V	2	2	2	0	6	$(x, 2, 6, 7)$	5
	Mean	1.50	1.67	1.56	0.72	5.44		5.39
	Mean (rounded)	2	2	2	1	5		5

7. Summary and conclusions

So far, there has been no coherent method for assessing the environmental impact of applying a specific construction innovation by experts and associated with this method way of estimating the level of risk of incorrect assessment. The need to develop such a method resulted from the demand to increase innovation in the construction sector in Poland. For this growth to happen, decision-makers must have the right tools to support the decision-making process in applying innovation.

The adopted criteria for assessing the impact of innovation on the environment resulted from the need to implement EU policies in the field of environmental protection, in particular climate protection, by Poland. Therefore, the cumulative consumption of primary energy was chosen because Poland needs to achieve the objectives of the Energy Efficiency Directive. Cumulative CO_2 emissions were selected because Poland and the entire EU strive to achieve climate neutrality in 2050, and the construction sector plays a leading role in this strategy. Waste minimization was selected as the evaluation criterion, as it is a crucial problem for implementing the circular economy. Drinking water resources in Poland are among the smallest in Europe, hence the criterion of minimum water consumption.

One may wonder whether the adopted four criteria fully reflect the impact of innovation on the environment. The authors of the method believe that these criteria are sufficient. Still, the assessment system can always be extended with additional measures, e.g., the impact of technology on the ozone layer or dust emissions. The accuracy of the method and the extent of the risk of making wrong decisions about the application of innovation depends on the data available to the evaluators.

The research shows that it is easier and more accurate to assess material solutions with the proposed method than innovative installation, technological or organizational solutions.

The proposed systems for assessing innovation (in integer numbers and fuzzy numbers) give similar results. However, the scoring system based on fuzzy numbers shows the degree of uncertainty in the evaluation mainly due to the expert approach to assigning values to individual evaluation criteria. The integer classification system shows no uncertainty in the assessment. Therefore, the system of evaluating total innovation should be mainly used by engineers. They have to make decisions to select the technical solutions with the highest reliability concerning the adopted criteria. On the other hand, the fuzzy number rating system is ideal for decision-makers, managers, and investors who tend to make investment decisions without going into detail and, therefore, with some risk.

The appropriate selection of innovations to test the evaluation method and ways to estimate the risk of a wrong decision resulted in the fact that the research revealed various doubts about the quality of the proposed tools, such as the selection of appropriate experts performing assessments, availability of complete information about innovation, appropriate reference level to the currently dominant technologies in the field of innovation implementation. In some innovations, the ratings of industry experts slightly differed from those of other experts. This was related to the scope of information available. Despite all these problems, it can be concluded that the proposed author's method of expert assessment of the environmental impact of construction innovations and the method of estimating the level of risk of incorrect assessment combined with this method may be used by the decision-maker for the initial selection of innovations.

References

[1] S. Firląg, et al., "Główne aspekty środowiskowe związane z budynkami biurowymi", in Zrównoważone budynki biurowe, PWN, Warsaw, Poland, 2018.

[2] A. Kaliszuk-Wietecka and A. Węglarz, "Nowoczesne budynki energoefektywne". Polcen, 2019.

[3] J. Bizon-Górecka, "Innowacje w budownictwie i ich ryzyko". Przegląd Budowlany, vol. 78, pp. 43–47, 2007.

[4] A. Węglarz and M. Pierzchalski, "Comparing construction technologies of single family housing with regard of minimizing embodied energy and embodied carbon". E3S Web of Conferences 49, 2018.

[5] A. Sapińska-Oeliwa, et al., "Porównanie metod oceny oddziaływania budynków na środowisko – wkład Laboratorium Geoenergetyki Wydziału Wiertnictwa, Nafty i Gazu AGH w rozwój metodologii". Energy Policy Journal, vol. 17, no. 11, 2014.

[6] A. Panek, "Holistyczna metoda oceny oddziaływania obiektów budowlanych na środowisko naturalne uwzględniająca zasady rozwoju zrównoważonego – raport końcowy projektu 8 T07G", Poland, 2005.

[7] K. Martinek-Jaguszewska, "Zarządzanie ryzykiem w procesie wdrażania innowacyjnych usług – przegląd literatury i konceptualizacja modelu". Studia i Prace Kolegium Zarządzania i Finansów/Szkoła Główna Handlowa, vol. 151, 2016.

[8] V. Singh, "BIM and systemic ICT innovation in AEC: Perceived needs and actor's degrees of freedom". Construction Innovation, vol. 14, no. 3, pp. 292–306, 2014, DOI: 10.1108/CI-02-2013-0006.

[9] G.E. Gürcanli and U. Müngen, "An occupational safety risk analysis method at construction sites using fuzzy sets". International Journal of Industrial Ergonomics, vol. 39, no. 2, pp. 371–387, 2009, DOI: 10.1016/j.ergon.2008.10.006.

[10] X. Xue, et al., "Innovation in construction: A critical review and future research". International Journal of Innovation Science, vol. 6, no. 2, pp. 111–125, 2014, DOI: 10.1260/1757-2223.6.2.111.

[11] A.R. Fayek and K. Hampson, "Leveraging Innovation for Sustainable Construction". Proceedings of the CIB Task Group 58, pp. 18–19, 2009.

[12] P. Dewick and M. Miozzo, "Sustainable technologies and the innovation – regulation paradox". Futures, vol. 34, no. 9–10, pp. 823–840, 2002, DOI: 10.1016/S0016-3287(02)00029-0.

[13] P. Davis, et al., "Assessing construction innovation: theoretical and practical perspectives". Construction Economics and Building, vol. 16, no. 3, pp. 104–115, 2016.

[14] Autodesk, "Budownictwo innowacyjne. Wizja liderów branży 2025". Report, Poland, 2019.

[15] M. Krechowicz, "Metodyka zarządzania ryzykiem w budownictwie podziemnym infrastruktury miast". Przegląd Organizacji, vol. 4, pp. 28–37, 2020.

[16] U. Kulatunga, D. Amaratunga, and R. Haigh, "Construction innovation: a literature review on current research". University of Huddersfield, Reprints, United Kingdom, 2006.

[17] B. Ozorhon, et al., "Innovation in construction: a project life cycle approach". Salford Centre for Research and Innovation in the Built Environment (SCRI) Research Report, vol. 4, pp. 903–1012, 2010.

[18] "10 innovative construction materials that could revolutionise the industry." [online]. Available: https://www.letsbuild.com/blog/10-innovative-construction-materials.

[19] "What are new innovations in construction?" [online]. Available: https://www.quora.com/What-are-new-innovations-in-construction.

[20] "10 innovations that have revolutionized construction." [online]. Available: https://constructible.trimble.com/construction-industry/10-innovations-that-have-revolutionized-construction.

[21] O. Ogunbiyi, A. Oladapo and J. Goulding, "Construction innovation: the implementation of lean construction towards sustainable innovation". Proceedings of IBEA Conference, Innovation and the Built Environment Academy, 2011.

[22] M. Coccia, "Measuring the impact of sustainable technological innovation". International Journal of Technology Intelligence and Planning, vol. 5, no. 3, 2009, DOI: 10.1504/IJTIP.2009.026749.

[23] L. Nazarko, "Technology assessment in construction sector as a strategy towards sustainability". Procedia Engineering, vol. 122, pp. 290–295, 2015, DOI: 10.1016/j.proeng.2015.10.038.

[24] C. Sjöström, et al., "Sustainable Smart ECO-Buildings". Proceedings of IBEA Conference, Innovation and the Built Environment Academy, 2011.

[25] S. Mjakuškina, M. Kavosa and I. Lapina, "Achieving Sustainability in the Construction Supervision Process". Journal of Open Innovation: Technology, Market, and Complexity, vol. 5, no. 3, 2019, DOI: 10.3390/joitmc5030047.

[26] B. Jefferson, S. Judd, and C. Diaper, "Treatment methods for Grey Water". Decentralised Sanitation and Reuse: Concepts, Systems and Implementation". Book, London, UK: IWA, 2001.

[27] P. Narloch and P. Wojciechowski, "Assessing cement stabilized rammed earth durability in a humid continental climate". Buildings, vol. 10, no. 2, pp. 1–20, 2020, DOI: 10.3390/buildings10020026.

[28] P. Narloch, et al., "Flexural tensile strength of construction elements made out of cement stabilized rammed earth". Procedia Engineering, vol. 111, pp. 589–595, 2015, DOI: 10.1016/j.proeng.2015.07.049.

[29] J. Fangrat and J. Sieczkowski, "Budownictwo innowacyjne". Builder, vol. 21, 2017.

Analiza ryzyka w ocenie oddziaływania na środowisko innowacji budowlanych

Słowa kluczowe: BMS, innowacje inżynierskie, środowisko, liczby rozmyte, trójkątna funkcja przynależności

Streszczenie:

W niniejszej pracy skupiono się na ocenie oddziaływania na środowisko innowacji stosowanych w budownictwie oraz określeniu ryzyka podjęcia błędnej decyzji o zastosowaniu w praktyce innowacyjnej technologii. Zdecydowano się na porównanie innowacyjnych technologii w budownictwie poprzez określenie wielkości: skumulowanej energii pierwotnej, śladu węglowego, odpadów nie możliwych do dalszego efektywnego przetworzenia, zużycia wody w cyklu życia budynku w porównaniu z odpowiednimi wielkościami dla obecnie najczęściej stosowanych technologii. Można się zastanawiać czy przyjęte tylko cztery kryteria w pełni oddają wpływ innowacji na środowisko. Autorzy metody uważają, że te kryteria są wystarczające, ale zawsze system oceny można rozbudować o dodatkowe kryteria np. wpływ technologii na warstwę ozonowa lub emisję pyłów. Dla każdego z czterech przyjętych kryteriów zaproponowano dwie skale ocen, które mogą służyć do analizy ilościowej i porównania analizowanych innowacji. Pierwsza skala opisana jest w liczbach całkowitych z przedziału od –2 do 2, a druga w liczbach rozmytych o trójkątnej funkcji przynależności.

Ocena w liczbach całkowitych jest podawana zgodnie z następującą skalą wpływu na środowisko: ocena "–2" – negatywny wpływ, ocena "–1" – niewielki negatywny wpływ, ocena "0" – neutralny wpływ, ocena "1" – niewielki pozytywny wpływ, ocena "2" – pozytywny wpływ. Ocenę w liczbach rozmytych z trójkątną funkcją przynależności podano zgodnie z następującą skalą wpływu na środowisko: ocena "trójkąt $(x, -2, -2, -1)$" – negatywny wpływ, ocena "trójkąt $(x, -2, -1, 0)$ – niewielki negatywny wpływ, ocena " trójkąt $(x, -1, 0, 1)$ – neutralny wpływ, ocena " trójkąt $(x, 0, 1, 2)$ – niewielki pozytywny wpływ, ocena "trójkąt $(x, 1, 2, 2)$" – pozytywny wpływ.

Ocenę końcową danej technologii innowacyjnej stanowi suma ocen cząstkowych dokonanych przez ekspertów dla czterech kryteriów oceny. W przypadku oceny w liczbach całkowitych będzie to suma arytmetyczna w przypadku oceny w liczbach rozmytych będzie to suma trójkątnych liczb rozmytych. Wynikowej ocenie została przypisana odpowiednia interpretacja obrazująca poziom pozytywnego lub negatywnego oddziaływania na środowisko oraz w przypadku łącznej oceny w trójkątnych liczbach rozmytych wielkość ryzyka błędnej oceny.

Metodę oceny innowacji i ryzyka przetestowano na 4 następujących technologiach: ziemi ubijanej, odzysku wody deszczowej z modułem oczyszczania wody, wykorzystania robotów w budownictwie i budynków inteligentnych. Przykłady zastosowania metody oceny innowacji i sposobu oszacowania ryzyka tej metody dobrano tak aby przeanalizować główne etapy w cyklu życia budynku, czyli: etap projektowania, etap budowy oraz użytkowania.

Dokładność metody i wielkość ryzyka podjęcia błędnych decyzji o zastosowaniu innowacji zależy od informacji jakimi dysponują oceniający. Z badań wynika, że łatwiej i trafniej jest ocenić przy pomocy zaproponowanej metody rozwiązania materiałowe niż innowacyjne rozwiązania instalacyjne, technologiczne lub organizacyjne.

Odpowiedni wybór innowacji do testowania metody oceny i sposobów oszacowania ryzyka błędnej decyzji sprawił, że w czasie badań ujawniły się różne wątpliwości dotyczące jakości działania proponowanych narzędzi takie jak: dobór właściwych ekspertów wykonujących oceny, dostępność do pełnej informacji o innowacji, właściwy poziom odniesienia do aktualnie dominujących technologii w obszarze wdrażania innowacji. Oceny ekspertów branżowych nieznacznie odbiegały w przypadku niektórych in-

nowacji od ocen pozostałych ekspertów. Było to związane z zakresem dostępnych informacji. Mimo tych wszystkich problemów można wysnuć wniosek, że zaproponowana autorska metoda eksperckiej oceny oddziaływania na środowisko naturalne innowacji budowlanych oraz połączonego z tą metodą sposobu oszacowania poziomu ryzyka błędnej oceny, może służyć decydentom do wstępnej selekcji innowacji.

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