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Analysis of the Energy Balance of Constructions Based on Wood during Their Use in Connection with CO_2 Emissions

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Abstract: In the construction industry, it is the material production phase and the use phase of buildings' life cycles that represent the greatest environmental burden. The presented research focused on wood constructions during their use phase. The primary objective of the research was to determine the amount of CO_2 produced during the operation of specific wood constructions in connection with the energy demand for their heating. A correlation analysis of selected parameters revealed a statistically significant correlation between heating medium type and energy demand for heating ($p = -0.5773$) and between heating medium type and amount of CO_2 produced ($p = 0.4796$). A more detailed analysis showed that, in terms of the average energy demand for heating, the column constructions were the most efficient among the compared construction systems, regardless of the energy standard. Similar findings were obtained for annual CO_2 production in connection with the average energy demand for heating. The only difference was that the panel and log constructions exhibited almost identical parameters, which came as a surprise to some extent. The column constructions turned out to be the most efficient again, regardless of their energy standard. The analysis that focused on the heating medium type revealed statistically significant differences among the heating medium types in energy demand for heating ($p < 0.0001$). The constructions that used electricity for heating were the most energy-efficient. When the individual characteristics of the different heating media in relation to CO_2 production were taken into account, the constructions that were heated using biomass were the least polluting. The constructions heated using electricity and gas showed a significantly greater deviation.

Keywords: carbon dioxide; energy; sustainability; use phase; wood construction

1. Introduction

The Fifth Assessment Report in the Intergovernmental Panel on Climate Change [1] states that in the past 50 years human activity has warmed the Earth more than ever before. Much of the warming effect is contributed by the burning of coal, oil and fuel and deforestation and intensive farming [2]. The construction industry is another major contributor. Buildings and other constructions consume enormous amounts of non-renewable natural resources during their life cycles, whether during the production of construction materials or their transport, construction operation or recycling [3]. In addition, the conversion of agricultural and forest land into built-up areas has a negative effect on biodiversity, animal populations and the overall regional climate [4,5]. Environmental aspects play an important role in all construction investment projects.

The carbon footprint, as a subset of the ecological footprint, is one of the indicators of the overall impact of human activity on the environment. The carbon footprint is the volume of the man-made emissions of those gases that have an impact on the Earth's climate [6]. Although there is no unified definition of carbon footprint, a narrow and a broad definition are generally distinguished. A calculation of the carbon footprint in the narrow sense may treat carbon dioxide as the only greenhouse gas, include other gases containing carbon (e.g., methane) or even include gases with a greenhouse effect that do not contain carbon (e.g., nitrous oxide). Likewise, the definitions of the human activities whose impact should be taken into account may also vary. Some may only consider direct activities, which include the use of internal combustion engines and electricity consumption [7,8]. The broad definition also considers emissions produced during the entire life cycle of products and services—from raw material acquisition to waste disposal. The units in which the carbon footprint is stated also vary. It can be stated as the weight of carbon, as the equivalent of the weight of CO_2 (eCO_2) for all greenhouse gases or it can be stated in hectares of growing vegetation capable of absorbing the given amount of greenhouse emissions [9]. Industrial production is one of the areas of human activity with a significant impact on the environment. The research also implements certain activities that effectively map and collect data for subsequent evaluation and adoption of such measures that would improve performance and sustainability as such [10–13]. In the construction industry, it is the material production phase and the use phase of buildings' life cycles that represent the greatest environmental burden.

The construction industry is responsible for 30% of the overall energy consumption and more than 55% of final electricity consumption. Around 1% is consumed during construction, 84% is consumed during use and 15% is consumed by construction materials [14]. Although the progress made in the construction industry towards sustainable buildings is a positive phenomenon, it struggles to keep up with the growing demand for energy supply services in the sector. The quality of buildings and their energy efficiency are of crucial importance for society [15–17]. The construction industry is characterized by very long life cycles, which calls for immediate action to reduce energy consumption and CO_2 emissions [18]. This equally applies to new and renovated buildings. The specific action the building construction sector should focus on is the introduction of modern and energy-efficient technologies such as building insulation, thermal pumps and energy-saving lighting. Consumer behavior and building operation are no less important, which can also significantly reduce energy consumption [19].

Materials should be selected according to durability and impact on health, their distance from the source, renewability and possibility of recycling without a reduction in quality [20–22]. Concrete is the second most commonly used material in the world after water. Its production remains a highly energy- and material-intensive process [23,24]. If the use of concrete is necessary, at least its more ecological variant based on blended cement should be preferred, as its production consumes less raw materials and produces less CO_2 emissions [25–28].

The construction industry makes increasing use of natural and renewable materials such as wood, clay and straw and insulation from wool, hemp, cork, wood and cellulose [29]. This is due to their beneficial effects on the internal environment and human health. Natural materials create the feeling of comfort, are typically sourced locally, and consume little energy during production [30–33]. Green roofs are now gaining in popularity in Slovakia, as they are more durable, help improve the microclimate in summer and reduce stormwater run-off.

Construction solutions based on wood are a response to the sustainability trend. Modern ecological wood constructions can compete with traditional solutions based on concrete, silicates, steel and other conventionally used materials [34–36]. Wood is an ecological and renewable material, i.e., it is created in a natural process and perishes without negative effects [37].

Wood is a basic material that was already used by our ancestors to build dwellings thousands of years ago. They understood how useful a material wood was. There was enough of it, it was easy to process, and it protected them against rain and frost. Wood has not been the preferred option in certain regions, with investors preferring projects using prefabricated blocks and bricks [38]. At the same time, as a growing number of investors come to appreciate the benefits of wood, more ecological solutions are beginning to establish themselves [39,40]. The use of wood as the main construction material is not possible for all types of structural solutions. It has statics-related and technological limitations depending on the limit conditions of its use [41]. The main barrier to more extensive use of wood in construction in Slovakia is a certain degree of prejudice and poor awareness of wood constructions among investors and constructors [42,43]. This research paper seeks to contribute to the promotion of constructions based on wood and evaluate actual experience with wood constructions based on analyses of existing constructions.

Ecological construction is construction that creates healthy conditions for life and sustainable housing development by building more eco-friendly constructions [44,45]. The completion, operation, disposal and restoration of ecological constructions also help protect the environment. Ecological construction requires a practical attitude (on the part of the user, the architect, the constructor and the construction supervisor), thoroughly prepared construction-technological project documentation and practical observance of ecological principles and criteria in the completion, use, maintenance, disposal and restoration of ecological construction products.

As mentioned at the beginning, the construction sector is among the sectors with the highest share in the total energy consumption. The largest amount of this energy is consumed during the use phase, i.e., as much as three quarters, compared with just one quarter consumed during the construction phase and the construction material production phase. It is for this reason that this research focused on analyzing the use phase in the life cycles of existing wood constructions. The objective of the research was to determine the amount of CO_2 produced during the operation of specific wood constructions in connection with the energy demand for their heating.

2. Materials and Methods

The object of the research were wood constructions in actual use, which were examined to determine their operating costs and energy balances during the use phase. The information about the specific energy balances and operating costs was obtained from their users. Seventy-three wood constructions were included in the research. The research sample consisted of constructions using prefabricated sandwich panels, constructions using the column construction system and constructions using the log construction system.

The constructions were examined to determine the cost of their operation and the amount of energy required during their use. The constructions were categorized according to their construction system and their energy standard. The energy standards were categorized according to the following characteristics: energy-saving house (80.4–150 kWh/m^2.a), low-energy house (40.7–80.4 kWh/m^2.a), ultra-low energy house (20.4–40.7 kWh/m^2.a) and passive house (heat demand for heating/cooling (HD) max 20.4 kWh/m^2.a) [46].

As the objective of the research was to determine the amount of CO_2 produced during operation as a result of the constructions' energy demand for heating, it was also necessary to obtain information about the types of heating media used in the individual wood constructions. The investigated buildings were subjected to a more detailed in situ analysis and examined in terms of types and kinds of heating systems. These findings, together with the monthly and annual energy consumption, were the basis for deriving individual characteristics for the calculation of CO_2 production. The wood constructions were surveyed to determine their operating costs and energy demand in relation to CO_2 production characteristics [47]. To maximize the informative value of the results, the volumes of the individual media were calculated per m^2 of useful floor area.

The basic descriptive statistical methods extended to include the Spearman correlations and ANOVA Kruskal–Wallis test were used to analyze the obtained data.

2.1. Examined Wood Construction Variants

A description of the individual construction methods used to build the examined wood constructions is included in the subsections below.

2.2. Prefabricated Sandwich Construction System

The prefabricated sandwich construction system is currently the most popular and most wide-spread type of wood construction in Central Europe. An assembled house built from sandwich wood panels (Figure 1) is virtually indistinguishable from a masonry construction, whether from the outside or the inside. The main characteristic trait of a panel system construction is that it allows maximum preparation of constructions in production and quick assembly and completion at the construction site. The structure of the panels consists of wooden frames thickly coated with suitable large-area materials. The space inside the frame is filled with thermal-sound insulation. Chipboard, OSB board, wood fiber gypsum board, wood fiber cement board or other materials are used for the coating. The panels' wood frames are structurally adapted to their function, i.e., to be used as external walls, partition walls, ceilings, roofs or floors [48,49]. The panels can be manufactured with different degrees of finish, from thick frames coated on one side with a large-area material to panels with built-in windows and doors, with a final finish of the interior and exterior side with built-in wiring. They can be different sizes, with large machinery used for their assembly [50].

Figure 1. Prefabricated sandwich construction system [51].

2.3. Column Construction System

The structure of the column construction system (Figure 2) originates in the US and Canada. The original American "two by four" system uses two timber sizes, i.e., 50 mm × 100 mm for columns and 50 mm × 200 mm for lintels, ceiling beams and rafters. The profiles' axes are 400–600 mm apart [52]. Columns with a cross-section of 50–60 mm × 120–160 mm are currently used in Slovakia (to accommodate thicker thermal insulation). The profile height determines the thickness of the insulation filling. The columns run from the sill plate to the top plate, with ceiling beams let into them (balloon frame system) or framed separately and placed onto the top stud of the frame (platform frame system) [53]. In Slovakia, this construction system has been modified to some extent in line with legislative requirements, the requirements of investors and manufacturing possibilities.

Figure 2. Column construction system [54].

2.4. Log Construction System

The traditional log construction system (Figure 3) is characterized by a log structure of external and partition bearing walls under a visible beam ceiling on the interior and exterior side [55]. The structure of the beam ceiling holds the truss structure, which is left visible on the outside or in the interior, according to the requirements. The log construction system is not insulated from the outside—the valuable, architecturally impressive and attractive log structure is left visible, showing the beauty of the wood, the dimensions, the structural design and wood craftsmanship [56]. The gaps in log walls and angle joints (external wall corners, external walls and partition walls, walls and the ceiling, etc.) are sealed using various methods. Only the gaps of a single-layer external wall are sealed —insulation is not applied to the whole surface of the wall. An external log wall with a brick lining is insulated and protected against moisture.

Figure 3. Log construction system [57].

3. Results and Discussion

The constructions whose parameters were examined in the analysis were categorized according to construction system type, energy standard and heating medium type.

The correlation analysis (Table 1) revealed statistically significant correlations between the following parameters: heating medium type and energy demand for heating (p = −0.5773), heating medium type and amount of CO_2 produced in relation to the heating medium type required for heating (p = 0.4796), energy demand for heating and amount of CO_2 produced in relation to the heating medium type required for heating (p = 0.3149) and energy demand for heating and energy standard (p = −0.3049). Based on the identified correlations stated in Table 1, the individual data were categorized (see Tables 2–11) and were studied in more detail using the ANOVA statistical method.

Table 1. Correlation analysis of selected parameters regardless of the construction type of the constructions.

	Heating Medium Type	Energy Demand for Heating [kWh/YEAR per m^2]	Amount of CO_2 Produced in Relation to the Heating Medium Type Required for Heating [kgCO_2/YEAR per m^2]	Energy Standard
Heating medium type	1.0000			
Energy demand for heating [kWh/YEAR per m^2]	−0.5773 ***	1.0000		
Amount of CO_2 produced in relation to the heating medium type required for heating [kgCO_2/YEAR per m^2]	0.4796 ***	0.3149 **	1.0000	
Energy standard	ns	−0.3049 **	ns	1.0000

Note: ns, not significant, ***, extremely significant 0.0001, **, very significant 0.01.

Based on the analysis shown in Table 2, it can be stated that the energy demand for heating in the individual energy standards varies, but the statistical analysis did not reveal statistically significant differences ($p = 0.0532$).

CO_2 production in relation to the individual energy media is also related to energy demand for heating. The analysis stated in Table 3 reveals differences in relation to the energy standards of the examined constructions. These differences were not statistically significant ($p = 0.1233$). Tables 2 and 3 are related, but the differences among the energy standards in Table 3 are not as significant as those in Table 2. This may also be due to the fact that the individual analyzed wood constructions used different heating medium types, which, as a result, changes the ratio of energy demand for heating to CO_2 production.

Table 2. Annual energy demand for heating categorized according to energy standards calculated per m^2 of useful floor area of the analyzed wood constructions regardless of the construction system.

[kWh/YEAR per m^2]	Energy-Saving Standard (n = 9)	Low-Energy Standard (n = 42)	Ultra-Low Energy Standard (n = 12)	Passive Standard (n = 10)
average	111.31	84.68	77.98	49.68
± std	64.63	50.10	62.93	25.77
min	40.71	17.22	14.23	18.81
max	213.33	196.40	246.15	94.67
median	85.45	66.19	68.76	45.76
perc. 25%	68.78	48.77	38.16	36.24
perc. 75%	157.63	114.88	91.32	53.58
ANOVA	$p = 0.0532^{ns}$			

Note: n, number of subjects; ns, not significant.

Table 3. Annual CO_2 production in relation to heating categorized according to energy standards calculated per m^2 of useful floor area of the analyzed wood constructions regardless of the construction system.

[kgCO_2/YEAR per m^2]	Energy-Saving Standard (n = 9)	Low-Energy Standard (n = 42)	Ultra-Low Energy Standard (n = 12)	Passive Standard (n = 10)
average	24.30	14.23	15.37	9.35
± std	23.94	8.94	9.71	5.61
min	6.99	2.91	5.49	3.62
max	85.33	42.68	33.88	19.80
median	20.47	12.54	11.60	9.12
perc. 25%	10.25	7.24	7.81	5.07
perc. 75%	23.34	18.52	21.83	9.47
ANOVA	$p = 0.1233^{ns}$			

Note: n, number of subjects; ns, not significant.

Tables 4–9 present more detailed analyses of the energy demand for heating and the related CO_2 production in connection with the individual construction systems and energy standards.

Based on Table 4, it can be stated that the panel construction system did not show any statistically significant differences between the compared energy standards in relation to energy demand for heating ($p = 0.3450$).

Table 5 shows locally more significant deviations between the examined energy standards than Table 4, which is substantially influenced mainly by the heating medium type. These differences were not statistically significant ($p = 0.9155$).

Table 4. Annual energy demand for heating categorized according to energy standards calculated per m^2 of useful floor area of the analyzed panel wood constructions.

[kWh/YEAR per m^2]	Energy-Saving Standard (n = 5)	Low-Energy Standard (n = 20)	Ultra-Low Energy Standard (n = 6)	Passive Standard (n = 2)
average	102.38	77.10	81.60	93.49
± std	66.06	51.65	29.96	1.67
min	40.71	17.22	41.56	92.31
max	213.33	196.40	120.80	94.67
median	85.45	57.93	77.71	93.49
perc. 25%	69.93	43.75	64.69	92.90
perc. 75%	102.46	84.44	103.03	94.08
ANOVA	$p = 0.3450^{ns}$			

Note: n, number of subjects; ns, not significant.

Table 5. Annual CO_2 production in relation to heating categorized according to energy standards calculated per m^2 of useful floor area of the analyzed panel wood constructions.

[$kgCO_2$/YEAR per m^2]	Energy-Saving Standard (n = 5)	Low-Energy Standard (n = 20)	Ultra-Low Energy Standard (n = 6)	Passive Standard (n = 2)
average	26.32	16.66	15.02	9.35
± std	33.41	9.68	8.97	0.17
min	6.99	3.22	7.69	9.23
max	85.33	42.68	30.48	9.47
median	10.25	17.63	11.60	9.35
perc. 25%	8.55	8.31	8.67	9.29
perc. 75%	20.47	22.94	18.70	9.41
ANOVA	$p = 0.9155^{ns}$			

Note: n, number of subjects; ns, not significant.

Table 6, which presents the individual values of energy demand for heating for column construction types of wood constructions, shows more significant deviations, but these differences were not statistically significant either ($p = 0.0850$). An unexpected finding was recorded in the comparison of the energy-saving standard, the low-energy standard and ultra-low energy standard, where the findings contradicted the initial expectations. The passive energy standard showed the lowest energy demand, which is in line with the expectations.

The ratio of the energy standards presented in Table 7 has changed compared to Table 6, but these deviations were not statistically significant either ($p = 0.1746$). The energy-saving standard was the least efficient solution of all compared standards. These differences can be attributed to the sample sizes in the individual categories.

Table 6. Annual energy demand for heating categorized according to energy standards calculated per m^2 of useful floor area of the analyzed column wood constructions.

[kWh/YEAR per m^2]	Energy-Saving Standard (n = 2)	Low-Energy Standard (n = 14)	Ultra-Low Energy Standard (n = 3)	Passive Standard (n = 8)
average	63.57	78.82	92.85	38.73
± std	7.37	36.25	132.78	12.95
min	58.36	29.11	14.23	18.81
max	68.78	130.38	246.15	54.95
median	63.57	71.58	18.18	39.32
perc. 25%	60.97	49.18	16.21	32.78
perc. 75%	66.18	112.99	132.17	49.30
ANOVA	p = 0.0850 ^{ns}			

Note: n, number of subjects; ns, not significant.

Table 7. Annual CO_2 production in relation to heating categorized according to energy standards calculated per m^2 of useful floor area of the analyzed column wood constructions.

[kgCO_2/YEAR per m^2]	Energy-Saving Standard (n = 2)	Low-Energy Standard (n = 14)	Ultra-Low Energy Standard (n = 3)	Passive Standard (n = 8)
average	25.43	10.59	13.64	9.35
± std	2.95	6.97	9.56	6.36
min	23.34	2.91	7.16	3.62
max	27.51	30.27	24.62	19.80
median	25.43	10.72	9.15	7.25
perc. 25%	24.39	5.56	8.15	4.75
perc. 75%	26.47	12.20	16.88	11.67
ANOVA	p = 0.1746 ^{ns}			

Note: n, number of subjects; ns, not significant.

Only three energy standards are analyzed in Tables 8 and 9, as there were no passive standard log constructions. This confirms the current trend, i.e., that this type of constructions is not commonly built to the passive standard, as a passive log construction would be enormously difficult and expensive to build. As for the differences among the energy standards presented in Table 8, considerable differences can be observed, but these differences were not statistically significant (p = 0.1141).

Despite the findings presented in Table 8, where the differences among the individual variants were considerable, this ratio of the energy standards in Table 9 was different. Thus, even in this case, these differences were not statistically significant (p = 0.7321). In Table 8, the most efficient variant was the ultra-low energy standard, but, when recalculated to CO_2 production in relation to the specific heating medium, this variant, together with the energy-saving standard, produced the most CO_2 compared to the low-energy standard.

In terms of the average energy demand for heating regardless of the energy standard, the column constructions were the most efficient among the compared construction systems. The column constructions were followed by the panel constructions, and the log constructions were the least efficient. This was not surprising in the case of the log constructions and the expectations were confirmed. Log constructions represent a traditional wood construction method, often without the required additional thermal insulation. The panel wood constructions were a surprise to some extent, where a better result was expected. This is because panel wood constructions are the most modern construction system among the compared construction systems, characterised by, among other properties, a high degree of prefabrication to ensure as high a quality of construction as possible, with high-quality structural details and very good thermal-technical parameters. Compared to the panel construction system, column structures, made on-site, are less influenced by innovative factors during construction completion, so their construction efficiency is lower. Despite this, in terms of average energy demand for heating, the column constructions turned out to be the most efficient among the compared construction variants.

Table 8. Annual energy demand for heating categorized according to energy standards calculated per m^2 of useful floor area of the analyzed log wood constructions.

[kWh/YEAR per m^2]	Energy-Saving Standard ($n = 2$)	Low-Energy Standard ($n = 8$)	Ultra-low Energy Standard ($n = 3$)
average	181.38	113.90	55.87
± std	33.58	61.74	28.37
min	157.63	34.19	27.97
max	205.13	194.33	84.69
median	181.38	112.71	54.95
perc. 25%	169.51	63.58	41.46
perc. 75%	193.25	164.27	69.82
ANOVA		$p = 0.1141^{ns}$	

Note: n, number of subjects; ns, not significant.

Table 9. Annual CO_2 production in relation to heating categorized according to energy standards calculated per m^2 of useful floor area of the analyzed log wood constructions.

[kgCO_2/YEAR per m^2]	Energy-Saving Standard ($n = 2$)	Low-Energy Standard ($n = 8$)	Ultra-Low Energy Standard ($n = 3$)
average	18.14	14.53	17.81
± std	3.36	8.94	14.56
min	15.76	3.42	5.49
max	20.51	31.36	33.88
median	18.14	15.85	14.07
perc. 25%	16.95	6.97	9.78
perc. 75%	19.33	17.45	23.97
ANOVA		$p = 0.7321^{ns}$	

Note: n, number of subjects; ns, not significant.

Similar findings were obtained for annual CO_2 production in connection with the average energy demand for heating. The only difference was that the panel and log constructions exhibited almost identical parameters, which came as a surprise to some extent. The column constructions turned out to be the most efficient again, regardless of their energy standard.

Tables 10 and 11 present the analysis of energy demand for heating and the related CO_2 production in connection with the individual media required for heating regardless of the construction system or energy standard.

The analysis presented in Table 10 shows statistically significant differences in energy demand for heating in relation to the type of heating medium used ($p < 0.0001$). The constructions heated using biomass had the largest share in the sample, followed by the constructions heated using electricity, and the constructions heated with gas had the smallest share. The constructions heated using biomass were the least efficient solution in terms of energy demand for heating. The constructions heated using biomass were followed by the constructions heated with gas. The constructions that used electricity for heating were the most energy-efficient.

Based on the data obtained in the analysis of actual constructions, deviations were summarized, after performing the calculations presented in Table 11, in relation to CO_2 production during heating in connection with the individual heating medium types. The ratio in Table 11 is different from the ratio in Table 10, where statistically significant differences $p < 0.0001$ were also recorded. When the individual characteristics of the different heating media in relation to CO_2 production were taken into account, the constructions that were heated using biomass were the least polluting. The constructions heated using electricity and gas showed a significantly greater deviation.

Table 10. Annual energy demand for heating categorized according to heating medium type calculated per m^2 of useful floor area of the analyzed wood constructions regardless of the construction system.

[kWh/YEAR per m^2]	Electricity (n = 20)	Gas (n = 9)	Biomass (n = 44)
average	41.74	72.41	102.37
± std	17.95	55.67	53.29
min	14.23	22.51	29.11
max	84.85	213.33	246.15
median	41.13	57.93	88.88
perc. 25%	32.49	49.50	63.05
perc. 75%	53.37	68.78	127.62
ANOVA		$p < 0.0001$ ***	

Note: n, number of subjects; ***, extremely significant 0.0001.

Table 11. Annual CO_2 production in relation to heating categorized according to heating medium type calculated per m^2 of useful floor area of the analyzed wood constructions regardless of the construction system.

[$kgCO_2$/YEAR per m^2]	Electricity (n = 20)	Gas (n = 9)	Biomass (n = 44)
average	19.17	28.96	10.24
± std	10.29	22.27	5.33
min	4.23	9.00	2.91
max	42.68	85.33	24.62
median	18.45	23.17	8.89
perc. 25%	9.38	19.80	6.31
perc. 75%	26.84	27.51	12.76
ANOVA		$p < 0.0001$ ***	

Note: n, number of subjects; ***, extremely significant 0.0001.

It should also be noted that the analyzed constructions were used in a standard way, with comparable numbers of users, which contributed to more comparable data and more valid conclusions. The research may have been limited by the fact that not all compared categories had the same sample size, which may have affected the final result. It is therefore necessary to take this into consideration in future analyses. For the sake of obtaining the best and most objective results possible, it is necessary to increase the number of constructions, which would not only contribute to yet more valid conclusions but also expand knowledge of wood constructions. An important factor that may substantially affect both the energy balance and the financial aspect of the use of constructions are users and the way constructions are used. Inefficient use can have a significantly greater impact on the financial aspect and on the environment than economical and efficient use. This fact needs to be recognized by users for their own benefit. Users may own an energetically highly efficient construction, but if they do not use it efficiently and fail to exploit its benefits, their financial costs may be much higher than what is expected.

The limitations of this research can be attributed mainly to the complexity of data collection. Because obtaining data from users is often difficult and especially convincing them to cooperate, the survey and data collection often had to be carried out again because not all users were able to sufficiently map the operation of buildings without the assistance and training of the researcher. The direction and expansion of the research will be directed in the future to the expansion of the portfolio of monitored constructions. Thus, other alternative construction systems based on wood and also based on other building materials will be investigated. A possible extension to the future will be the incorporation of various characteristics such as local climate, energy source footprint, building insulation, building design, indoor temperature setpoints, etc. A more detailed study of operation and use will also be an important part of further research in this area.

In the area of efficient spending of resources, mainly environmental interests are leaning, but economic aspects as such are becoming more and more popular at all levels. Within the mentioned area, it is possible to apply various sensory, intelligent technological solutions [12] through which it is possible to obtain the necessary data for decision-making processes [13] leading to an intelligent society, sustainable behavior leading to economic growth [58].

Within research and activities, there are several works that deal with reducing the impact of human activity on the environment within modern trends in the carbon sequence [59–61]. Modern and innovative trends have become an integral part of today, and they are being implemented in almost all aspects of life. Several works have dealt with the research of modern trends in the economic contexts [62–65]. The starting point for research in these areas is to bring into the production sphere such solutions and trends that will contribute to sustainability and efficiency as such.

In the field of construction, specifically in the field of construction solutions, on the one hand, it is important to design such construction solutions that are not only energy efficient but also environmentally acceptable. On the other hand, it is possible to reduce the negative balance of construction solutions in other ways, such as the use of alternative energy sources [61] needed for the operation of buildings as such. Because the conventional energy sources used so far for the operation of buildings are often not environmentally friendly and in terms of global environmental impacts are not a sustainable alternative with the desired effect for modern design and engineering solutions [66], it is necessary to consider this level in the design of future efficient buildings.

The energy demand or efficiency of buildings is a topic that receives increasing attention, as does efficient and economical use of energy and financial resources during the operation of buildings. Production of CO_2, a greenhouse gas, is closely related to these topics in all aspects of life on earth. It is therefore necessary to keep expanding knowledge and awareness of these aspects, which ultimately influence the quality of the environment in which we live and create conditions for future generations. Few research works examine wood constructions from the same perspective as the presented research. The analyses of wood constructions in actual use in the presented research can expand knowledge of certain aspects of constructions based on wood.

The research by Seo et al. [67] analyzed the manufacturing, transport and construction phases and their environmental impact. The analyses in the research show that CO_2 emissions during the transport of materials and on-site construction represent 2.4% and 4.2% of the total CO_2 emissions. They concluded that it is important to choose suitable input materials and resources to reduce CO_2 emissions. As mentioned in the presented research, the material transport and construction phases represent a certain burden on the environment, but the burden is negligible compared to the material manufacturing and use phases. This is not a rule, as it depends on many factors, such as the materials used for construction and the construction method.

The research by Rolfsman [68] focused on ways to achieve a reduction in CO_2 emissions in various aspects of the use of constructions. The analyses in the research showed that raising the energy standard of a building by, for example, replacing windows with better quality ones and by improving the thermal-technical characteristics of the external coating can reduce the amount of energy resources required for the operation of the building. CO_2 production in connection the amount of energy resources used is also related to this fact. These claims are in line with the conclusions in the presented research, as one of the findings produced by the analysis of existing constructions was that the use phase and, more specifically, energy demand for heating are influenced by the energy standard of the given building. It is therefore necessary to design solutions that are efficient, with a positive impact on the environment.

Energy demand for cooling during summer months, in addition to energy demand for operation and heating, is also related to buildings' energy balance. In view of this, it is important to realize that if a building's envelope is designed correctly, in other words, if the external coating meets the required thermal-technical standards, it should be able to protect the energy inside the building during winter months and protect it against overheating during summer months. It is in this context that Radhi [69] examined the parallels between global warming and the energy demand of a building during summer months. The study concludes that a careful and correct design of a building and its structural details can achieve a reduction in energy demand for cooling to prevent the building from overheating. As a result, this can reduce energy demand on the cooling system and the related CO_2 production. Fahmy and Sharples [70] focused on similar problems, emphasizing the need to study not just the energy demand of buildings during winter months but also the energy balance of buildings during summer months in connection with the cooling of their internal environments. Every geographical region has different preferences as to the energy balances of buildings, so it is necessary to attach different degrees of importance to the matter depending on the region. The conclusions of the study are in line with the conclusions and experience in the presented work, gained during the research.

Gustafsson et al. [71] pointed out that measures to comply with the European Union directives involve implementing measures to save energy. The requirements of the directives constantly raise the energy standards and balances of buildings. The authors also examined the possibilities to reduce the energy balances of buildings in connection with heating. The use of so-called remote heating of buildings is mentioned as a possible solution. Their conclusion is that different measures to save energy influence the system of remote heating in different ways. Further, their results show that the use of a thermal pump for waste air affects electricity consumption and production in the system of remote heating the most, and measures to save energy lead to a reduction in electricity consumption in the building, a reduction in electricity consumption for heat generation in the system of remote heating and an increase in electricity production. Another conclusion of the research is that electricity consumption in a building is the most important factor to be considered in adopting measures to save energy and to reduce the related CO_2 emissions in energy production. It should be pointed out that, based on the experience in the presented research, although electricity may appear green in terms of CO_2 production in connection with its production, it is still not possible to prefer just this type of energy for all aspects. Several factors play an important role in selecting an energy medium for heating, from local policies to the global circumstances and the visions of transnational policies. The research by Guelpa et al. [72] focused on similar problems, i.e., efficient heating systems and their innovation potential. They concluded that a certain form of regulation, optimization and innovation of the regulation of energy resources and heating systems can reduce the energy balance of buildings, while preserving the limit conditions required for the use of buildings. Such efficient use of energy resources can reduce not only the financial costs of the operation of a building but also CO_2 production in connection with individual energy media.

The research by Rosselló-Batle et al. [73] analyzed buildings' life cycle phases in terms of CO_2 production. The objective of the study was to identify the processes and phases with the greatest impact on energy consumption and CO_2 emissions into the environment. The results of the research show that the operation phase, representing 70–80% of the total energy consumption, has the greatest impact. Another important finding in the research is that energy demand for the production of construction materials only represents 1/5 of the total energy consumption in the life cycle of a construction. This is in line with the findings in the presented research, which support and highlight the need for the deepening of knowledge in this field. Due attention should be paid not just to efficient solutions for the production of construction materials and construction but also to the operation phase of buildings.

The research by Ürge-Vorsatz et al. [74] examined, in a broader context, constructions and their impact on CO_2 emissions in a life cycle. The conclusion is that the operation of constructions substantially affects CO_2 emissions into the environment. The study also states that buildings and the buildings fund can play a key role in mitigating the effects of climate change in the short to medium term, as they can achieve a substantial reduction in CO_2 emissions in the coming years, provided that energy for the operation of constructions is used more efficiently. A significant share of these savings can be achieved by methods reducing costs during the life cycle, thereby reducing CO_2 emissions. This is in line with the findings in the presented research.

4. Conclusions

The presented research focused on wood constructions during their use phase. As the subject of efficient use of energy and CO_2 emissions into the environment receives increased attention, the objective of this research was to determine the amount of CO_2 produced during operation in connection with the energy demand for heating in specific wood constructions.

The correlation analysis of selected parameters revealed a statistically significant correlation mainly between heating medium type and energy demand for heating ($p = -0.5773$) and between heating medium type and amount of CO_2 produced in relation to the heating medium type required for heating ($p = 0.4796$).

A more detailed analysis showed that, in terms of the average energy demand for heating, the column constructions were the most efficient among the compared construction systems, regardless of the energy standard. The column constructions were followed by the panel constructions, and the log constructions were the least efficient. Similar findings were obtained for annual CO_2 production in connection with the average energy demand for heating. The only difference was that the panel and log constructions exhibited almost identical parameters, which came as a surprise to some extent. The column constructions turned out to be the most efficient again, regardless of their energy standard.

The analysis that focused on the heating medium type revealed statistically significant differences among the heating medium types in energy demand for heating ($p < 0.0001$). The constructions that used electricity for heating were the most energy-efficient. When the individual characteristics of the different heating media in relation to CO_2 production were taken into account, the constructions that were heated using biomass were the least polluting. The constructions heated using electricity and gas showed a significantly greater deviation.

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