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Research paper

Life cycle assessment of composite straw bale technology in residential buildings in the context of environmental, economical and energy perspectives – case study

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Abstract: Occurrences associated with the phenomena of climate change are increasingly visible. Effects of progressive environmental pollution are monitored with growing concern. Still, in the construction sector, the choice of sustainable materials and the knowledge concerning them is insignificant. Studies have shown that single-family residential buildings form the largest share of new buildings in Central European countries. It should be assumed that it is the improvement of this particular section of the construction sector to be the goal of further development of societies. This paper presents a case study of the construction of a house using straw - a material that, on the one hand, is a product associated with local tradition, while significantly reducing carbon footprint of its production and use, on the other. The construction of a prototypical house with the application of composite technology, i.e. timber framing with straw bale infill, was compared with a conventional method (ceramic masonry units) which is currently the most popular choice for building single-family houses in Poland. The study is based on the building's life cycle assessment (LCA) over its consecutive phases as a tested and reliable method of the verification of a material's impact on the environment.

Keywords: straw bale; CO2 reduction; Life Cycle Assessment (LCA), sustainable materials, market acceptance

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1. Introduction

1.1. Environmental impact of the construction sector

The construction sector is responsible for 30–40% of total global greenhouse gas emissions (1), while housing construction remains its important section, generating as much as 17% of the total global emissions (2). The assessment of a building's negative impact on the environment is performed using dedicated tools. One such tool is Life Cycle Assessment (LCA), which is based on assessing the entire life cycle of a building or that of its major elements. The division into individual stages associated with a building's construction and occupancy enables the determination of its carbon footprint in a broader view for a given project. Therefore, high CO2 emission comprises as much as 11% of global emissions and its impact on the environment applies to the construction industry, which is associated with, among others, the energy consumption of the manufacture of materials used in traditional construction (the fabrication of materials like brick, concrete, cement, steel, polystyrene). Furthermore, the construction sector consumes around 3 billion tons of natural resources every year, which is around 40–50% of the total resource demand (3). The excessive exploitation of natural resources, particularly for construction purposes, results in the production of millions of tons of construction and demolition waste (CDW) which, according to data provided by Eurostat, comprise around 25–30% of all waste produced in the EU. The Paris Climate Conference (2015), also known as the Paris Agreement, has considerably affected legally binding regulations concerning the climate. The EU government formed the first ambitious coalition and took steps that are to achieve the goal of lowering CO2 emissions by 40% by 2030 (4). In 2018, Poland hosted the COP24 UN Climate Summit (informal name for the 24th Conference of the Parties to the United Nations Framework Convention on Climate Change) aimed at discussing the challenges stated and formulated by the Paris Agreement. Research findings presented during the conference indicate that 25–30% of CO2 emissions generated by buildings is produced by materials and their production. Meanwhile, the remaining 70–75% were caused by the long-term use of buildings. That is why, it is critical to stimulate demand for solutions that reduce carbon footprint across the entire life cycle of buildings.

1.2. Contemporary housing in Poland

Energy-efficient houses are becoming an increasingly large group among ongoing projects. The term “energy-efficient house” can denote low-emission houses, sustainable housing, green building, passive houses, nearly zero-energy buildings and plus-energy buildings (5). The main direction of the pro-ecological movement in Poland is the pursuit of reducing primary energy. After 2021, single-family houses to be designed in Poland will have to achieve a PE indicator (non-renewable Primary Energy) of 70 kWh/(m2•annum). In 2019, out of over 192 thousand buildings that were handed over in Poland, almost 92 thousand were single-family houses (6). Buildings are built primarily using traditional technologies, using materials with very high thermal insulation parameters. Studies indicate that it is necessary to reach a compromise based on acknowledging the fact that to improve thermal insulation parameters and efforts to increase the thickness of thermal insulation material layers, it is beneficial to introduce new, often unconventional materials (7). The use of bio-based products is therefore an important aspect of reducing the carbon footprint in the construction sector. In Poland, the development of bio-construction applies to a small group of buildings and is limited due to the popularity of traditional technology, the prevailing opinion about bio-construction's high cost or distrust of new technologies.

Table 1. Analysis of various types of thermal insulation for an envelope element with a thermal resistance ofR=5.0 [(m2K)/W] and a heat transfer coefficient of U = 0.2 [W/(m2K)], without accounting for surface resistances Rsi Rse. Source: 2, 3 on the basis of manufacturers' technical cards. 5,6 based on data prepared by institutions associating individual producers, such as EURIMA, and research results published by the non-profit organization BSRIA (Building Services Research and Information Association) (ICE DB V1.0; ICE DB V2.0 and ICE DB V3.0 databases).

1	2	3	4	5	6
Material	**Thermal conductivity λ** *[W/(mK)]*	**Material density** *[kg/m³]*	**Material layer thickness for R=5.00 [(m2K)/W]** *[cm]*	**Embodied energy per 1m2 of envelope element R=5.00 [(m2K)/W]***[MJ/m²]*	**Carbon footprint per 1m2 of envelope element R=5.00 [(m2K)/W]** *[(kgCO₂e)/m²]*
Straw bale	0.052	80.0	26.00	18.512	-26.0000
Sheep wool	0.036	20.0	17.95	104.110	1.7950
Glass wool	0.032	21.5	16.00	96.320	4.6440
Rock wool	0.036	95.0	18.00	287.280	19.1520

Wooden houses, with either a timber frame or log structural system, are chosen by 8.4% of persons who build houses in Poland, constituting the most numerous group among those who prefer technologies alternative to traditional construction (8).In a period of unfavorable climate change, timber buildings undoubtedly have a positive impact on reducing embodied energy and the carbon footprint across the entire life cycle and demolition (9). Kozłowski J. indicates that lesser wooden conductivity allows for the reduction of the number of materials used to insulate insulating materials whose production causes chemical pollution as well as CO2 emission (10). Eco-friendly building, apart from energy efficiency, means healthy materials. That is why, in the case of timber buildings, doubts concerning ecology are raised by products used as infill for the timber frame. Every material with a long life cycle minimizes the number of repairs or refurbishment, thereby reducing costs, the amount of material consumed, and thus lowers the amount of carbon footprint. A comparative analysis of materials used as thermal insulation infill in timber frame buildings demonstrates that mineral and rock wool is characterized by a much higher Embodied Carbon (EC) than in the case of straw bale, whose EC value is negative (Table 1).

1.3. Straw as a building material

In many developing countries, sustainable (green) native materials are used to support the demand for safe housing. Examples include employing straw bales in Northeastern China, bamboo in Ecuador, and earth roofs in Africa (11). Jenny Pickerill argued that the economic and social potential of eco-friendly houses is weakened due to their poor design (12). The author believes that the design of eco-houses requires accounting for climate factors, cultural traditions, available materials, lifestyle needs and local skills. She claims that there is a need for research to trace the path of a project to its use, not only from the designer's point of view, but also that of residents. The application of straw bale technology in Poland also appears to be more of a return to the roots rather than a new trend. In Poland, the use of straw, clay or wooden planks is dated back to the tenth century and was the basis for erecting the first Slavic gords or gontynas associated with deities (13). Along with the appearance of Christianity, these oldest works of architecture in Polish lands were destroyed. During subsequent centuries, wood and straw-based construction developed as vernacular architecture and was associated with the first churches (14). The dense forests that were prevalent at the time were ample sources of material. The oldest techniques of weaving and molding walls were gradually replaced by timber building using clayed straw (non-flammable thatch), as roofing or the technique of erecting walls based on filling timber frames with straw wrapped around wooden planks and covered with clay from both sides (15). During later periods, several instances of the return to clay-based and straw-based construction could be observed in Poland: always during times when increased construction demand (e.g. after a war) could not be fully satisfied by conventional masonry construction due to a deficit in construction materials, energy or funds. Such situations occurred after the First World War, after 1939 and after the conclusion of the Second World War. This final return of clay-based construction to Poland was a fully technically and organizationally modern construction movement, modeled on German solutions (16).

Straw obtained for construction purposes may have a different origin (from a farmer, an industrial plant). 29 million tons of straw are produced in Poland every year, with most of it being grain or rape straw. At present, due to the mechanization of agriculture, straw surplus is at around 12.9 million tons per year (17). Hance, it does not have a technical assessment by accredited laboratory. In Poland, straw cubes can be used in construction as a product approved for singular use in a structure, as it is stipulated in the Construction Products Act of the 16th of April 2004 (Dz. U. No. 92 item 881 as amended). It is noted that the use of a natural and renewable material that is obtained directly from plants contributes to reducing CO2 emissions and alleviates climate change, while also creating an environment that is friendly to humans. It also has implications for certification schemes (such as BREEAM and Passive house), which push the boundary of what is considered best practice, whereas government policy must steer towards a more holistic understanding of sustainable building design beyond a narrow focus on energy and carbon emissions. BREEAM gives attention to the implementation of all measures for the optimization and effective use of building materials at all stages of the investment, from the design stage, through delivery, to maintenance and service (18). Further work may expand the sampling method to seek out radical practice beyond the scope of mainstream architectural recognition. This may include a consideration of communities who simultaneously embrace innovative technologies combined with low impact lifestyles (19). The greatest benefit to the use of straw in construction is its potential associated with embodied energy and minimal impact on the environment across its life cycle. In their paper, B. Sodagar et al., compared building elements made using different technologies and their impact on CO2 emissions, clearly indicating that replacing materials with renewable ones can lead to benefits not only during construction, but also in the case of a 60-year-long use period (20). At the same time, studies have confirmed that in the case of its use there is no greater threat of fire, pest attack, damp or mold growth than in the case of conventional materials. User fears of using straw bale on the example of Japan were discussed in a paper by K. Holzhauter and K. Itonagi who analyzed a wall under different thermal conditions and exposed it to strong atmospheric effects, as humidity is very high in that country, which allows us to assume that these were conditions considered extreme. The authors used existing local buildings as a basis They noted the issue of building a layered wall so that an air gap could be created to facilitate air circulation. This demonstrated the behavior of a building with passive ventilation, analyzed via measurements using temperature and hygrothermal condition sensors which operated within the wall (21). Numerous authors employed comparative analysis, comparing a traditional and alternative material - in this case straw bale. One example is a paper by Bakhoum E. S., et al., whose authors investigated the functioning of a wall with straw bale and concrete masonry units in a small prototype built for research purposes. The comparison was performed for 3 phases of the building's life cycle: production, construction and demolition, while also assuming the testing of the material's pollution emission, the energy required to produce it, its potential for reuse and user satisfaction during use. In the comparison, straw bale returned a zero-level result, with the exception of the production phase, as it required energy and machinery to produce the bale. This is also an example of the application of straw as to create a block that can be used for insulation, and thus allows one to reduce emissions via the self-application of the material as an infill in a timber frame house. Both the concrete masonry unit and the mineral wool insulation, and polyurethane foam insulation in particular, displayed highly unfavorable results. They achieved the highest energy consumption and CO2 emission parameters. When material reuse was considered, straw bale likewise displayed favorable results, allowing for a 100% processing rate without energy consumption and no carbon footprint. The matter was different with mineral wool and polyurethane foam, as only a small percentage of these materials can be recycled (22). Brojan L., et al. presented a comparison of partitions made with the use of straw bale and brick, primarily noting the high energy cost during the production and transport phases. The authors highlighted the benefits of using straw as a construction material, as it means the use of natural waste - a material that is no longer needed. Its reuse is therefore an additional benefit. Straw bale technology allows for the safe use of straw, meeting standards expected of contemporary construction materials. In their comparison, the authors built a straw-bale wall with a thickness of 47 cm with a single layer of straw, while the two-layer brick wall had a width of around 57 cm had a ceramic structural layer and was insulated using EPS polystyrene. Both partitions had the same RTotal-value: around 8.30 (m2K)/W. The benefit in the form of a lower wall thickness, which allowed the achievement of 3% of additional floor area, was clearly visible. The straw bale wall was also observed to be lighter than the ceramic wall. Building such a wall also takes less time, which also translates to a lower energy consumption overall (23).

2. Case study

The case under study was the construction of a single-family house built in southern Poland in the years 2017–2020, to present the potential of composite technology that combines straw bale with timber framing, which is a solution that combines tradition and innovation. A married couple who were visual artists by profession, fascinated with the ecological proposals of sustainable building, asked employees of the Cracow University of Technology to design a house for them that would meet the criteria of an eco-friendly building. The design team, who was comprised of architects and structural engineers under the supervision of Marta Fąfara, proposed a combination of a commonly used timber framing technology with a solution that was both historical and innovative in Poland, that is straw bale. The primary goal of the study was to compare the technology with conventional construction materials (ceramic masonry units) in terms of 3 pillars: **environmental, economical and social terms.** An additional advantage was the possibility of using the global trend known as Do It Yourself (DIY) - important to people's relationships and their sense of committing the act. For people who want to perform their own home repairs and renovations homes may be more homely when they are made from materials which the owners have the skills to work with (24).

Fig. 1. Photographs taken during construction and of already built house in Raciechowice, Malopolska, author Marta Fąfara, 2017-2020

The building was designed to feature two levels, without a basement. Its structural system was comprised of transverse timber frames formed by branching columns located within the plane of external walls, roof trusses and deck beams. A frame distance of 90 cm was assumed due to the necessity to provide space for roof windows and straw bales. The design initially featured the joining of structural elements via angled brackets. However, they proved to be too costly during the early stage of construction and were replaced with nails and traditional wood joinery. The selection of the structural system and design details was performed following the principle of ensuring ease of construction for persons without construction experience. External walls featuring straw infills are characterized by a relatively large thickness, which typically exceeds 35 cm and is dictated by thermal insulation requirements. In the case of the house the thickness of external walls was 45 cm - straw bales with a width of 45 cm, a height of 40 cm and a length of 45 cm were used. It was necessary to determine the dimensions of individual straw bales during the design phase, so that the distances between structural elements could be designed in such as a way so as to require as little cutting of the straw bales as possible during construction. Walls of such considerable thickness resulted in the necessity to build foundation walls up to a height of 30 cm above grade to prevent the straw from damp caused by rainfall. The building features reinforced concrete foundation walls with a thickness of 30 cm, with the timber structure being extended outwards by 15 cm relative to its external surface. The site on which the building was built was characterized by good quality clay (which was elastic and oily), which was collected on-site to be used. In this study the end of life stage of the building could not be investigated.

2.1. First pillar - environmental

For the purposes of calculations, thermal conductivity was used on the basis of manufacturers' technical cards, which is λ=0.052 (however, the worst thermal conductivity coefficient for straw bales listed in the literature is λ =0.086 W/(mK) (25). The thermal resistance of a straw layer with a thickness of 45 cm for the cautiously estimated λ-value, was R = 5.23 (m2K)/W. To achieve the same thermal resistance with mineral wool, a layer with a thickness of 18–23 cm would have to be used, depending on λ = 0.035-0.045 W/(mK). Based on digital models and the project under study, the authors calculated the amount of construction materials consumed. The listing of materials used for each technology has been presented individually (26). The authors prepared calculation models to highlight and display the significant differences in CO2 emissions for the construction components used in the construction of buildings using traditional and composite methods. To determine the energy certificate the method of calculation of 2015 has been applied. For the purposes of analysis, the authors assumed boundary conditions that enabled the side-by-side presentation of the technologies under study in terms of energy. The partitions of both buildings were modeled so as to achieve the same heat transfer coefficient in all corresponding envelope elements. When modeling thermal bridges and sensitive connections, the authors assumed a simplified model scheme so that the calculation parameter would be the same for both technologies. In order to present the most realistic analysis of the facility's operation, the authors used primary energy taking into account all energy loads in the building. Concluding with the final energy calculation, the entire pillar B of the LCA would be omitted. After preparing two identical calculation models, the authors assessed primary energy demand (PE). Based on a primary energy of EP=71.40 [kWh/(m2annum)], the authors assessed the amount of emitted CO2. The energy carrier was assumed to be natural gas. The calculations undertook the application of a heat pump with a nominal power output of 17.6 kW. The application of this system caused a lower energy consumption. The analyses were used to produce quantitative listings of materials used for each technology, which were paired with the information necessary for total life cycle assessment during each of its phases. Trade reports that list the energy consumption of materials and kgCO2e emissions in the products display discrepancies in the published EE and EC coefficients. This is why the authors used the most up-to-date and reliable coefficient values which accounted for carbon deposits in the material. When calculating carbon footprint [kgCO2e] and embodied energy [MJ] values accounting for the manufacture of the product, the authors used the technical documentation of each product, which include information of additional data, such as the material's thermal conductivity coefficient, density, consumption, and grammage. In the study, the authors used data prepared by institutions associating individual producers, such as EURIMA, and research results published by the non-profit organization BSRIA (Building Services Research and Information Association) (ICE DB V1.0 ;ICE DB V2.0 and ICE DB V3.0 databases). On the basis of the above data the value of the embodied energy index and the carbon footprint index have been adopted for calculations.

Table 2. Cumulative energy comparison [MJ].

Life cycle phase	**Cumulative energy *[MJ]***	
	Composite house (straw bale)	**Typical house (ceramics)**
A1-A3 production stage	1 961 245	1 727 606
A4 construction stage (transport)	955.4584	955.4584
A5 construction stage (construction)	5 500.77	12 607.2249
B4 use stage – replacement	126 251	126 251
B6 energy consumption over a 50-year life cycle	5 153 652	5 153 652
Total	**7 127 414**	**6 900 882**

Table 3. Cumulative carbon footprint comparison [kg CO2 e].

	Carbon footprint *[kg CO2 e]*	
Life cycle phase	**Composite house (straw bale)**	**Typical house (ceramics)**
A1-A3 production stage	16 055	110 786
A4 construction stage (transport)	70 820	70 820
A5 construction stage (construction)	610	1 315
B4 use stage – replacement	6 060	6 060
B6 energy consumption over a 50-year life cycle	313 117	313 117
Total	**456 105**	**551 541**

The life cycle assessment was based on actual distances between construction material suppliers and the construction site. The home improvement store used by the contractor was at a distance of 7 km while the concrete plant was at a distance of 20 km and the stone quarry that supplied the aggregate was at a distance of 10 km. Wood for construction was sourced from a local sawmill located at a distance of 40 km away from the construction site. The analysis assumed that, over a 50-year long life cycle, it will be necessary to perform the replacement of windows, doors, the gas boiler, the heat recovery equipment and photovoltaic panels once. To account for this, the authors added additional embodied energy and carbon footprint to the B4 use phase (26). EE and EC coefficients were sourced from ICE V1;V2;V3 databases.

2.2. Second pillar - economical

The authors studied the precise costs of the construction of the building up to its shell state, built using the composite technology under study (26). The house under study was built using straw produced as triticale cultivation waste (due to its toughness and small amount of seeds after processing), which was procured for a total of PLN 2 000, including transport. The straw was sourced from a farm located 7 km away from the construction site. One often-used manner of decreasing costs is to minimize the cost of professional labor, which in the case of the construction of houses from straw is often replaced by the owner's own labor and volunteers. In the case under study, the clients employed a construction company to perform most of the work. The DIY (Do it Yourself) trend is gaining more and more in popularity. It allows you to save money on professionals, and some of the work does not require professional knowledge and experience. The Internet is full of tutorials or mini guides where beginner builders can exchange their experience. The disadvantage of such a solution is probably longer duration of activities and exceeding working hours. The satisfaction that we created the house ourselves is also priceless.

Finally, the clients only filled in the timber framing with insulation made of straw and applied clay plaster. They worked in their spare time and managed to save PLN 25 000 by performing this work by themselves. This value was listed on the basis of costs presented by the construction company.

Table 4. Cost and savings comparison [PLN].

	Cost *[PLN]*		
	Composite house (straw bale)	**Typical house (ceramics)**	**Savings**
Material cost	207 818	242 029	**34 210**
Construction cost	50 000	75 000	**25 000**
Total	**257 818**	**317 029**	**59 210**

2.3. Third pillar - social. Comfort of use

In order to ensure adequate sanitary conditions inside the building, the use of materials containing excessive amounts of radioactive elements and materials containing formaldehyde and other volatile organic compounds should be eliminated. When using one own's building materials that one has obtained, such as clay, one should test the sample on the site to check if it is contaminated. The radioactivity of construction materials are defined by two parameters: f1 and f2. Activity index f1 informs us of the risk of total-body exposure to gamma radiation by K-40 potassium isotopes, Ra-266 radon isotopes and Th-228 thorium isotopes. The value of these parameters is dependent on the concentration of these isotopes expressed as Bq/kg. The safety condition is met when $f1<1.2$. Activity index f2 informs us of the concentration of the Ra-226 radium isotope, with the safety condition being $f2<240$ Bq/kg. In Poland, the study of the radioactivity of construction materials is performed by the Central Radiological Protection Laboratory (CLOR). Studies have demonstrated that the difference between the radioactivity of clay and ceramics is small. However, it should be remembered that bio-based materials like wood have an activity index of zero.

Table 5. F1 and F2 activity indices in selected raw materials and construction products (average values have been listed in parentheses), based on studies by CLOR 2012.

Type	**No. of samples**	**Activity index f1**		**Activity index f2[Bq/kg]**	
Clay	116	0.12–1.39	(0.61)	6–161	(48)
Ceramics	2148	0.11–1.63	(0.64)	8–176	(53)

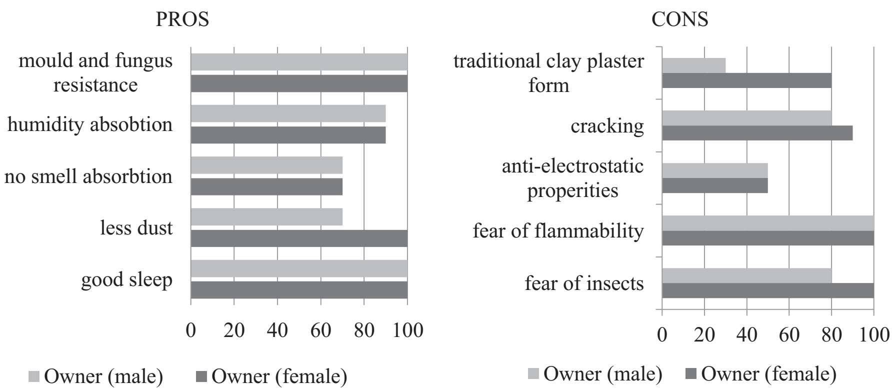

Fig. 2. Subjective resident opinions.

In addition, the authors performed an indoor environment study based on an interview with the building's residents. The clients admitted that the non-standard microclimate inside the building is owed to its composite structure and the use of clay plaster. The conversation was conducted with the users of the house that had been living in the house for 23 months. The family previously lived in a single-family house, built in traditional technology, located approximately 7 km away. There is no mechanical ventilation in both buildings. They were asked to list the pros and cons of the house built using composite technology. Afterwards, the interviewees were asked to rate them on a scale of 1–100%, where 1% denoted insignificance and 100% denoted high significance.

3. Discussion

As shown by the study, the construction of a house using the composite technology, generated 94.731 kg less CO2 during the material production stage than the typically used technology, with the total savings across the entire building's life cycle amounting to 95.436 kg. As shown by Gaj K. (27), in Poland, 1 ha of a 54-year-old pine forest can accumulate 30 tons of CO2. This means that a house built using traditional technology requires as much as 18.4 ha of pine forest across a 50-year-long life cycle, while a house built using composite technology requires 15.2 ha. During the life of the material, the amount of carbon is the same in nature all the time. When the uptake of CO2 by "a growing material" is not taken into account, carbon footprint analysis of natural materials results are comparable to modern materials or sometimes even worse. Therefore, another important problem should be discussed: the emission and production of other chemical compounds during the production and disposal of processed materials / building components. Performing the GWP (global warming potential) analysis shows a number of additional poisonous chemicals emitted into the atmosphere during their production. An additional problem is the utilization or recycling of the produced materials. Long chemical bonds are problematic to deactivate and again require high energy expenditure which generates the production of CO2 and other compounds. On the other hand, the utilization and recycling of straw is less invasive to the environment, as straw bales and the compounds they contain can serve as a nutrient and building material for flora.

The opinion that the design and construction of an eco-friendly house is much more expensive than the construction of a typical one, due to costly innovative solutions, is popular in Poland. Indeed, as demonstrated by the latest studies, the construction of a green-certified house is still more expensive, despite the premium on rent or maintenance highlighted in the literature. The main reason for this is the still-costly structural system, which has not been replaced by a high-performance green technology (28). In the case of single-family houses, the application of a composite system incorporating a timber frame made from locally-sourced wood and straw bale infill solves the problem of a costly structural system, as this study shows. Building construction costs depend on local conditions, the state and nature of the economy and the availability of craftsmen. The cost of the thermal insulation material itself is a small share in the total construction cost, but it remains of great benefit to both the environment and the occupant of the home.

Composite technology and the application of timber framing with straw bale as infill allows the achievement of contemporary standards of indoor environment quality. In an individual building one can and should pay attention to not only the proofing means one uses, but also the origin of construction materials including their radioactivity. As humans are not equipped with any senses that could warn them of excessive ionizing radiation, it is necessary to control it already at the stage of construction product selection (29). The application of natural materials minimizes the adverse impact of ionizing radiation as it is assumed that materials like straw or timber do not emit harmful radiation. The use of natural products can also favorably affect the microclimate of building interiors (i.e. by reducing volatile organic compounds). The application of clay plaster from the inside due to its excellent absorptive properties makes it easier to maintain proper indoor air humidity. Clay plaster has anti-static properties and, as reported by house owners, it results in there being less dust inside the house. Clay plasters do not suffer from mold or fungi growth. Properly milled straw does not contain weeds or other organic substances, which makes it rodent-free and prevents it from rotting.

Contemporary standards also affect the selection of the house's form. It should be remembered that the archetypical image of a straw house is that of a small, single-level cabin with a traditional appearance (small windows, eaves and a stone base). Those who opt to build eco-friendly houses are primarily people who are educated in the field and those who display high ecological awareness (30). Based on the interview with clients and designers, it was demonstrated that there are also other barriers on the Polish market, such as the lack of skilled personnel, the lack of understanding by the public, additional design requirements (the verification of a house's fire safety solutions). These concerns were also confirmed by a survey performed among the construction community of Great Britain (architects, civil engineers, construction company owners). The authors of this paper indicate that the low popularity of eco-friendly building stems from high construction costs, lack of knowledge, skills and understanding, chiefly on the part of designers, and their fear caused by professional responsibility and unclear legal regulations (31).

Concerns connected with the use of straw bale, which appeared both in the surveys and constituted the area of scientific research, were related to the use of the product, e.g. exposure to atmospheric conditions, susceptibility to mold or fungus. Despite the fact that it is a natural and biodegradable product, under proper conditions, the process of degradation either does not progress or is considerably slowed. Clean and dry straw has fewer nutrients; that is why it is not used by pests or insects as a food source, which was also among the fears of potential consumers. Social fears associated with the flammability of straw bales were proven to be unfounded, as the authors referred to the tests performed by the American Society for Testing and Material and confirmed that, due to the density of straw bale and restricted air availability, the material has an above-average fire resistance. Straw bale is also characterized by very high thermal insulation parameters due to the accumulation of energy and heat. It should be noted that well-dried straw is a long-lived material which means that after walls made from it need not be replaced and users need not worry about it becoming damaged. The biggest disadvantage of straw bale is its design limitation. Prefabrication would make it possible to obtain products analogous to the popular ceramic brick, but still an additional structure, e.g. wood, is required to obtain the expected span of the structure. Otherwise, only small areas would be possible.

4. Conclusions

Based on the results of this study, it was concluded that the use of composite technology in the construction of single-family houses might be an opportunity for the developing ecological construction market in Poland. Buildings built using composite technology display considerable potential to the ecological footprint not only through the materials used to build them, but also by the eco- and environmentally friendly behaviors of their residents. The characteristics and parameters of the house and particularly its insulation properties and construction costs allow us to acknowledge the trend of combining technologies and material solutions as an opportunity for the popularization of pro-environmental tendencies in single-family buildings in Poland.

This paper presents the key physical characteristics of straw bales. When appropriately made and stored, straw bales display parameters that enable them to compete with popular wall thermal insulation materials like mineral wool or expanded polystyrene. The case/prototype presented in the paper confirms the argument that thanks to the application of composite technology straw does not necessarily have to be associated with the traditional architecture of the end of the nineteenth and the beginning of the twentieth century, but can be an interesting alternative to contemporary building technologies.

There are still poor studies that explore the practical application of straw bale in contemporary housing construction in Poland. This paper demonstrates that straw bale can be implemented in single-family house construction while maintaining modern architectural form and offering additional benefits. The application of straw bales directly results in the improvement of the natural environment and the indoor environment of buildings, supports local economies, allows one to lower energy costs during every life cycle stage and does not cost more than traditional technology. Associated with the use of straw bale, client fears partially arise from lack of knowledge or access to it by potential buyers and associating straw buildings solely with extravagant architecture, as well as from limited access to professional construction craftsmen. In the subsequent study, the authors will present an extension of the GWP analysis and conduct a computer simulation of the durability of building elements using straw and selected traditional technologies. The popularization of straw bale construction will allow the monitoring of the impact of buildings on the environment during their use and the general trends in user satisfaction.

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Ocena cyklu życia technologii straw bale w budynkach jednorodzinnych w aspekcie środowiskowym, ekonomicznym i energetycznym - studium przypadku

Słowa kluczowe*: straw bale, redukcja CO2; ocena cyklu życia (LCA), zrównoważone materiały, akceptacja rynku*

Streszczenie:

Z coraz większą uwagą przyglądamy się zjawiskom związanym ze zmianami klimatycznymi, coraz bardziej widocznymi, ale również odczuwalnymi psychofizycznie skutkami postępującego zanieczyszczenia środowiska. Temat rozwiązań przyjaznych środowisku przestał być jedynie ciekawostką, ale stał się realnym zagadnieniem, które podejmowane jest w wielu dziedzinach życia społeczeństw oraz dyskusji ogólnoświatowych. Począwszy od sposobu pozyskiwania surowców, poprzez gospodarkę i wiele sektorów przemysłowych. Nie inaczej jest również z budownictwem. Badania pokazują, że największy procent powstających budynków w krajach Europy środkowej stanowią budynki mieszkalne jednorodzinne. Należy założyć, że to właśnie poprawa tej części sektora budowlanego powinna stanowić cel dalszego rozwoju społeczeństw. W branży budowlanej wybór zrównoważonych materiałów i wiedza o nich wciąż nie jest duża. Pokazują to ankiety, które zostały wykonane również w ramach niniejszego artykułu. Jednocześnie wybór takich produktów na wczesnym etapie projektowania domu, porównując ich parametry, pozwala prowadzić do zmian w kierunku realizacji zrównoważonego budownictwa. W założeniu dalszego rozwoju ekologicznych postaw społecznych, ale przede wszystkim spodziewanych, bo już dziejących się zaostrzeń związanych z prawnymi regulacjami m.in. Unii Europejskiej możemy spodziewać się, że wybór materiałów ekologicznych będzie celem przyszłości. W oparciu o tę obiecującą tezę artykuł prezentuje przykład studium przypadku budowy domu z wykorzystaniem słomy - materiału, który jest z jednej strony produktem związanym z tradycją lokalną, ale również wpływającego znacząco na redukcję śladu węglowego przy produkcji i eksploatacji. Przykład budowy prototypowego domu z wykorzystaniem mieszanej technologii tj. konstrukcji drewnianej z wypełnieniem z bloczka ze słomy został porównany z konwencjonalną, najczęściej wybieraną formą budowy domów jednorodzinnych w Polsce (bloczkiem ceramicznym). Badania opierają się o analizę podczas faz oceny całkowitego cyklu życiu (LCA), jako sprawdzonego i wymiernego sposobu weryfikacji wpływu materiału na środowisko. Na ich podstawie stwierdzono, że zastosowanie technologii mieszanej w budowie domów jednorodzinnych może być szansą dla rozwijającego się rynku budownictwa ekologicznego w Polsce. Budynki te wykazują znaczny potencjał w zakresie śladu ekologicznego nie tylko ze względu na użyte do ich budowy materiały, ale także poprzez proekologiczne zachowania ich mieszkańców. Charakterystyka i parametry domu, a w szczególności jego izolacyjność oraz koszty budowy pozwalają uznać trend łączenia technologii i rozwiązań materiałowych za szansę na upowszechnienie proekologicznych tendencji w budownictwie jednorodzinnym w Polsce. W artykule przedstawiono najważniejsze cechy fizyczne słomy. Odpowiednio wykonane i przechowywane bloczki ze słomy charakteryzują się parametrami, które pozwalają konkurować z popularnymi materiałami ocieplającymi ściany, takimi jak wełna mineralna czy styropian. Przedstawiony w artykule przypadek / prototyp potwierdza tezę, że dzięki zastosowaniu technologii kompozytowej słoma niekoniecznie musi kojarzyć się z tradycyjną architekturą końca XIX i początku XX wieku, ale może być ciekawą alternatywą dla współczesnych budynków jednorodzinnych.

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