Aspects of Reversibility and Energy Efficiency of Prefabricated Straw Structures – Guidelines for Sustainable Design of Architectural Interventions of 21st Century

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Abstract. Architectural space of the 21st century confirms, for the umpteenth time that, architecture is a personified image of society: The products of architectural interventions are the final creations in time and space. The whims of the market, the linear economy model, and users' pluralistic needs generated by cultural preferences mutually develop "white elephants" - inert material, useless and expensive to deconstruct. In response to social, environmental, climate, and economic changes, the construction sector needs to revalue existing construction techniques. The lack of broader application of the circular economy model, the use of inorganic materials and chemical bonds in architectural structures, due to the loss of cultural significance or the appearance of natural disasters, are deprived of their function and produce a large amount of waste. Therefore, the reuse of organic materials derived from renewable energy sources is becoming essential for pushing further the boundaries of reversible design and energy efficiency in architectural interventions. Limits of use of the old – new materials - compressed straw are defined by comparing the results of thermal properties of the building envelope elements - U and R values and levels of reversibility through two opposite approaches to construction, on the example of the conceptual design of a housing unit affected by natural disasters. Analysing the three levels of reversibility that 21st century buildings should possess, given the existing research, the material level limit is shifted in terms of returning to nature with potentially zero environmental waste. Comparing the results of the R values of prefabricated straw structures with the R values of materials predominantly used in architectural interventions raises awareness of the importance and benefits of using compressed straw in architectural envelopes. Existing design parameters of straw structures are optimized by valorising the importance of local climate and materials used. The interaction of native - cellulosic materials breaks down dogmas related to this material and generates the architectural language of reversible and energy-efficient architectural straw products.

1. Introduction
The architectural space of the 21st century again confirms that architecture is personified image of society. Architectural interventions' products are treated as final creations in time and space, without the possibility to change or deconstruct. Whims of the market – a linear economy model, technology, and pluralistic needs of users generated by cultural preferences take turns in appearing by influence on the creation of “white elephants” – inert material (waste) useless and expensive for deconstruction. The data on the lifecycle of buildings in the 21st century and International Energy Agency (IEA) data for 2019 confirm that none of these permutations are harmless. According to these data, the construction
sector makes 36% of the total energy consumption and 39% of the total CO\textsubscript{2} emission, of which 11% is the result of construction materials production, such as steel, cement, and glass.

What should be done in the future?

The profession seeks the PAUSE and/or the UNDO button in architectural language that is ready for changes (growth) – reversible design [1-6] based on the circular economy model. The architecture of the 21st century cannot be linear – exclusively the creation; on the contrary, it should be in the constant flow – creating, while the end of life should be perceived as creating – deconstructive, and not necessarily as a destructive act. Awareness of mortality should be the premise throughout which an architect – designer approaches the architectural intervention in space (moment of the construction of an idea is also a moment of the deconstruction of the idea) [7]. The absence of wider application of the circular economy model leads to draining out the resources, thus conditioning price increase of raw material, energy, and a larger amount of construction waste. Usage of inorganic materials and chemical bonds in architectural structures that lose their function due to loss of cultural significance or in cases of natural disasters, make a large amount of waste. Reuse of organic materials in architectural interventions is the key to pushing the limits of contemporary buildings sustainability. That is why it is necessary to reorganize the culture of building by revalorizing native building techniques and materials that save energy, that are economically sustainable, locally available, and environmentally friendly. Knowing that vernacular construction techniques and materials have limited range, considering the pluralistic needs of the 21st century buildings, does not mean that these should be avoided entirely and considered as “out of date.”

Compiling and comparing the results of thermal properties of building envelope elements – U-values and R-values and level of reversibility of linear building approach against the potential of “circular” on the example of a conceptual design of a residential unit [8] within site affected by natural disasters, the paper hereafter analyses the boundaries of an old-new way of building with compressed straw bales.

2. Reversibility - a tool to decrease CO\textsubscript{2} footprint

As a response to social, ecological, climate, and economic changes, the building sector is forced to revalorize the existing building techniques. Research [1-2] of Durmisevic E. (2006) compiles and analyses previous knowledge and alerts that it is high time to start designing buildings as systems that can be deconstructed and their components reused, processed, and put into new combinations (“to live other lives”). Existing buildings become raw materials for new construction – waste becomes a product. In reversible design, buildings are conceived as "material banks," systems made of parts separated through more levels following material loops and supporting users' and buildings' changeable needs for "growth." According to Durmisevic, there are three dimensions of reversible design: spatial, technical-structural, and material dimension. [2]. Through the first one, we follow building’s capacity to adjust to new spatial configurations. Through the second and third, we follow the ability of deconstruction of a structure with joint detail having a major role. For deconstruction to be possible, there must be a certain degree of independence between levels within the system. Interaction of subsystems, elements, and materials within the system should be realized with minimum interference of parts that are bearers of different functions. Each element should have one or a minimum number of related functions; otherwise, the deconstruction is more difficult and followed by absence of preservation of all members. For the process of deconstruction itself, the way of connecting the elements of a system is crucial.

We find the question of “reversible joint” in ancient societies [3] and recently in Modern Movement architects’ work. Since then, the usage of chemical bonds and inorganic materials based on the linear economy model in the context of long-term planning produces more damage than benefits. Although the usage of chemical bonds is not possible without previous destruction and changing the structure of the members of that bond, it does not have to apply a priori for organic materials.

Previous researches of dimensions of reversible design are focused chiefly on buildings of Industrial heritage. The results end with a deconstruction of subsystems to elements, with the recommendation for elements at the end of a lifetime to be included in processes analogous to recycling processes in order to reduce loss and CO\textsubscript{2} emissions. Considering that it is impossible to return elements made of inorganic
materials to nature, the question arises: Is there organic building material possessing a high level of return to nature?

2.1. Architectural dictionary of straw

If we return several centuries backward, in the 18th century, due to lack of wood, Nebraska's settlers were forced to start using a relatively neglected type of building with local organic material – straw, known as "Nebraska style." Soon afterward, cement's rising popularity occurred, which was proportional to the stagnation of building with straw. The straw was revived in the 20th century through the activities of the pioneers of straw building rebirth – the idea perpetuated through the Green Design approach. Since then, a great number of American and European countries set up building rulebooks \([9-10]\) – codes and official guidelines to regulate ways of usage. In countries where there is no formal acceptance in the form of codes, private organizations and institutes tend to promote innovative techniques through their activities. Still, these are daily suffocated by inert codes, building industry, bureaucracy, and uncritical – dogmatic beliefs.

![Figure 1. Architectural dictionary of straw products (c. [14]; d. [15])](image)

To open the way to wider application and overcome dogmas about this material, it is necessary to solve the problem evident in registers of an inherent attitude of building industry, human language, and architectural dictionary. “The game” of the label, labelled and the mental image of the given term in human consciousness equalizes the terms hay, straw, straw bales, and its hybrid products. Because of this and custom clichés, a man is always in delusion perceiving the straw as a bundle of scattered hay (rich in oxygen) (Figure 1.). A clear difference between hay, straw, straw bales, straw used in the building industry, and its hybrid products is given in building codes and specialized literature \([9-10]\). Technology development in the 21st century brings a rebirth of straw bales and its two archetype systems, a system of load-bearing and non-load bearing (straw as infill) walls, as prefabricated – modular hybrid panels, slab elements, and blocks (Figure 1.c.). Organic material (straw) communicates through hybrid language with inorganic materials, theoretically creating a complementarity discourse. The advantages of one material compensate for the other material’s limits. However, the practice shows the absence of complementarity – different chemical compositions of materials cause their degradation. In order to minimize the effect of different material response spectrum to the processes in architectural envelopes, a large number of air layers are placed, having thick envelopes as a consequence. To reduce the negative effects of intercommunication, it is necessary to create a hybrid assembly where cellulose-based organic materials – straw and wood, make 90% to 95% of total envelope volume. Although the load-bearing element entirely made of straw has not been patented yet, nor all the physical and technical performances of this material are fully known, a part of the previous research \([9-13]\) found the solutions for many problems that straw faced in the past.

Beliefs that straw products are susceptible to animal infestations, rapid flammability, storage – developing moisture and mold have no logical justification today. On the contrary, highly compressed straw bales used in an architectural dictionary of the 21st century:

- Increases fire safety of buildings. Compressed straw walls with a density of 120 kg/m\(^3\) and wall finishing of 1 inch have REI 120 label. \([11]\);
- Stores 60 times more carbon than used to grow, bale, and transport to building sites in the same region. Through the case study conducted in Heilongjiang province (2004), Kelly Lerner compares conventional houses made of bricks with the straw bales, showing that the straw bale system is 75% more efficient than conventional building systems. [12];
- Increases thermal performances of buildings. The California Energy Commission officially regards a plastered straw bale wall to have an R-value of 30. [12].

Prefabrication in the form of hybrid wall panels reduces the price and amount of workforce used to make 45% of the total expenses, thus contributing to the wider usage and acceptance of straw in the architectural language of the 21st century. The practice of placing the straw bales (Figure 1.d) into bearing timber frames generates fundamental elements of ecologically sustainable architectural design. Each element is designed for a specific function, and due to the mechanic bonds between system members, systems are qualified with a high degree of deconstruction.

2.2. Straw – aspects of reversibility
Natural disasters (mainly floods and landslides) that struck the Balkans in 2014 left behind a large amount of inert material, construction waste (Figure 2). Usage of inorganic materials combined with inorganic binders represents significant progress in the building industry. However, their interaction risks are rarely discussed, despite the increasing number of natural disaster victims. A large amount of inorganic waste and the inability to deconstruct such buildings without a vast sum of money alarms the need to redefine local and regional building cultures. The need for reversible, economically sustainable interventions that would minimize the environmental impact is extremely significant in cases of a periodic recurrence of natural disasters.

![Figure 2. Natural disaster in 2014 left behind large amount of inorganic waste](Figure 2. Natural disaster in 2014 left behind large amount of inorganic waste (Rečica - rural settlement, B&H)

The residential unit's concept design from (Figure 3) confirms that interventions of prefabricated cellulosic materials (straw and timber) can be highly reversible in time and space. The concept design provides the revitalization of contents harmed in natural disasters by constructing the sustainable residential unit. The initial functional area of the 50 m² residential unit is not final. Depending on their own needs, the users may do the horizontal widening to the extreme dimensions (max. 100 m²), with the size possibilities varying between the mentioned numbers. (Figure 3.a.)

Independence of bearing construction (LVL wood) of prefabricated panels filled with straw offers freedom of manipulation over the space. The aspect of spatial reversibility of the system "house inside the house" is reflected in the residential unit's divergent capability to a large number of permutations (≥ 60).
The needs of the time we live in require the chameleon ability of conversion of the existing and future buildings. The essence of reversibility as the philosophy of architectural intervention lies in the ability of its removal as if it never occurred. Thus, when choosing materials and construction systems that give a physical appearance to space, there should be awareness on reliance on the certain historical situation, which has a shorter life than physical form – intervention mark. Architectural interventions should have a high degree of reversibility of materials, structurally – technical reversibility of subsystems and elements. Usage of prefabricated hybrid panels combined with mechanical bonds and chemical bonds of organic origin makes the process of deconstruction easier if deconstruction is necessary. (Figure 3.b.)

![Figure 3. Dimensions of reversible design - conceptual design of a residential unit (Rečica - rural settlement, B&H)](image)

Recent examinations of the Agency for Statistics of B&H show that the total area of grain crops in 2020 was around 199.647 ha. There are 3 to 4 tons of straw staying after harvesting for each hectare of the area of grain crops. According to this calculation, in 2020, Bosnia and Herzegovina was left with 598.941 tons of straw in the fields after harvesting grain crops (wheat, rye, barley, and oat). If we take the analogy from the neighbors, counting that one-third of straw stays as ecological waste in the fields, then Bosnia and Herzegovina has around 399.294 tons of straw annually that can be used in the construction industry. Introducing the products of compressed straw into the construction industry material would reduce the pressure and need to use parts of inorganic material. Prefabrication of straw in modular prefabricated panels opens the possibility of using straw for ceilings and roofs.

A high degree of fire resistance, thermal efficiency, returning to nature through the processes similar to composting, zero CO\(_2\) emission are only part of indications of reversible behavior and energy efficiency of this material. At the same time, unlike conventional houses, straw bale houses are 5% cheaper, offer carbon sequestration, significant energy savings, and long-term savings (life cycle savings) associated with energy savings.

3. Straw – thermal properties of elements
Among three thermal motion methods through barriers, convection and conduction are the most important for straw bale structures. As a set of different lengths of hollow tubular structures, straw products allow passage of air and heat to a different extent, depending on the applied compression degree. The degree of compression applied in products depends on the spectrum of functions that the product will have. If the product is used as a load-bearing element, the degree of compression is higher than if it is used as an infill. Compression decreases the number of hollow spaces and increases density, where the dry density of straw must not be over 104 kg/m\(^3\). [9].
R-value as a quantitative measure of barrier resistance to heat in these systems can depend on age, type, moisture, the orientation of straw fibers 1, size, number of openings on the panel, thickness, and nature of surface layers. Researches such as the one at Oak Ridge National Laboratory (1998) show that structures with the straw bale orientation "on edge" have a higher R-value (R=1.45/inch) than the "flat" oriented. In prefabricated panels with flat orientation (R_{straw}= 17.86 m²K/W) [16], higher significance has the choice of surface layers and straw moisture percentage. If the moisture is higher than 20% of the total straw bale weight, degradation is certain to occur. It is necessary to control straw moisture before finishing layers, and then, as King B. [13], metaphorically explains, give the walls a good hat, pair of shoes, and coat that breathes. (Figure 4).

![Figure 4. Guidelines for the energy-efficient design](image)

The first guideline of the energy-efficient design “coat that breaths” refers to the usage of hermetically waterproof, windproof, and vapor-permeable membranes –Sd<0,2 m, that additionally reduce heat loss, prevents condensation while protecting the walls from weathering during the process of building. Membranes containing a high percentage of polyethylene and aluminium and surface layers such as stone, veneer sheets, and portland cement are not recommendable. The choice of surface layers has to depend on the climate. In the areas with a colder climate, outside surface layers should have a higher degree of vapor-permeability than inside surface. The most logical solution in a relatively dry climate is lime plaster outside, while the clay is inside. In stormy areas in the absence of deep eaves, it is necessary to use the ventilated façade system.

For one system to be energy-efficient, relations between its elements and subsystems must be realized without the appearance of thermal bridges. In the structures of "Nebraska style" systems, holes and gaps between straw bales are filled with additional straw flakes and then compressed, while membranes coat joints between walls and roof or walls and foundations. Membrane height matches the height of zinc coating to ensure better connection and load-bearing capacity of the whole system and the finishing layer using the chemical bond. Because of the usage of many heterogeneous materials and the absence of continued membrane coating, the "Nebraska style" system is exposed to thermal bridges' appearance, thus reducing walls' thermal performances. Technology progress and prefabrication process optimization reduce the number of inorganic materials used in this assembly. Today, membranes, steel pins, or other mechanical bonding elements are the only inorganic materials found in these structures.

Although the walls' thermal performances are far more researched than roofs and floor frame constructions, roofs' thermal performances in residential buildings have the most impact on buildings' thermal performances. A roof with deep eaves – "a good hat" represents the second guideline of the energy-efficient design of straw bale structures. Construction regulations in seismically active zones limit wider usage of straw in roof levels. Straw in roof levels represents additional weight which is necessary to be stiffened. Therefore, in seismically active zones, it is recommended to use alternative cellulose as an isolating material. In the zones with reduced seismic activity, straw bales usage is allowed with additional stiffening.

1 Straw fibers inside the panels can be "laid flat" and "laid on edge." In the case of "on edge" orientation, fibers' direction is vertical to the direction of heat motion, while in the case of "flat" orientation, the direction of fibers and heat motion is parallel.
If we look back a few years ago, not much importance was given to straw-infilled roofs and ceilings' thermal performances. The existing research fund finds the reasons for failure in a heterogeneous composition of the used materials. Due to different chemical and physical properties of the inorganic materials and straw, thermal bridges and straw decomposition occur. The highest degree of degradation occurs in the levels that are in direct contact with the foundations – ground. Straw decay occurs because of increased humidity and inability to dry. To prevent this, the building is distanced from the ground ("pair of shoes" - the third guideline), enabling ventilation of the ground-level. Air space exists between the building and the environment. (Figure 4).

4. Results and discussions

Three guidelines contained in the King B. sentence: Give the walls a good hat, boots, and a breathable coat, form the basis of the sustainable design of straw bale structures. Regardless of the levels in which are the layers of compressed straw, the adjacent layers are the ones that should enable straw to breathe. If the adjacent layers are vapor-tight and the percentage of moisture in straw increases over the critical limit of 20% of the total weight in straw bale structures, the degradation process begins. Thus, adjacent layers should be selected, and straw degradation processes prevented by analyzing the climate parameters.

| Layer thickness (cm) | R-value (m²K/W) (R=1/U) | λ (W/mK) | ρ (kg/m³) | Cₚ (J/kgK) |
|----------------------|------------------------|----------|-----------|------------|
| 10                   | 1,786                  |          |           |            |
| 20                   | 3,571                  | 0.056    | 110.00    | 2000.00    |
| 30                   | 5,357                  |          |           |            |
| 40                   | 7,143                  |          |           |            |

Table 1. R-values of prefabricated straw bale panels (according to EcoCocon [16] data).

The U and R values (Table 1. and Table 2.) of the thermal properties of compressed straw bale structures compared to the thermal properties of structures made of inorganic materials, open space for discussion about the advantages and potential of using them in building envelopes. Usage of straw, a locally available and economically viable material, reduces the pressure on using inorganic materials - large producers of CO₂.

The prefabrication process has a positive effect on generating a hybrid dictionary of modular units pushing the limits of use further. The presence of three dimensions of reversible design offers a wide range of possibilities for architectural interventions. The technical-structural dimension of the reversible design facilitates the deconstruction process in case of a periodic recurrence of natural disasters. Simultaneously, the ability to "return to nature" reduces the amount of waste that remains in space. Waste through processes analogous to the composting process becomes a product of future harvest, while hollow concrete blocks in the settlement affected by natural disasters (Figure 2) have been waste in space for seven years.

5. Conclusions

Reversible design in a time of natural disasters with the construction industry being one of the largest CO₂ producers is a positive way of thinking and the way forward into the future. The need for adaptable design - reversible architectural interventions that keep up with the requests of the 21st century seeks new - old, alternative solutions. Interaction of vernacular - cellulose materials, straw, and timber generates an architectural dictionary of reversible and energy-efficient architectural products, representing progress in energy efficiency and the circular life cycle of buildings. Optimization of the prefabrication process and mechanical bond usage enables a higher deconstruction degree, extremely important in natural disasters. Although mechanical bonds have the advantage of enabling faster deconstruction, chemical bonds with organic origin do not a priori imply the inability of deconstruction.
Table 2. U-values of building envelope components.

| Building envelope (components) | Layers of the building envelope (cm) (from the inside out) | U-value$^c$ (U=1/R) | Standard |
|-------------------------------|----------------------------------------------------------|---------------------|----------|
| WALL SYSTEM$^a$               | Gypsum lime plaster........................................ (2.0 cm) | 2.0                 |          |
|                               | Hollow concrete blocks...................................... (20.0 cm) |                    |          |
|                               | Cement-lime plaster........................................ (2.0 cm) |                    |          |
| WALL SYSTEM$^b$               | Lime plaster............................................... (2.0 cm) | 0.36                | $U_{\text{max}} = 0.35$                   |
|                               | Hollow concrete blocks...................................... (20.0 cm) |                    |          |
|                               | EPS insulation............................................... (8.0 cm) |                    |          |
|                               | Cement-lime plaster........................................ (2.0 cm) |                    |          |
| WALL SYSTEM$^c$               | Clay plaster................................................ (2.5 cm) | 0.18                |          |
|                               | Prefabricated straw bale panels........................... (30.0 cm) |                    |          |
|                               | Vapour permeable membrane (Sd<0.2 m)........................ (0.1 cm) |                    |          |
|                               | Cellulose fibre insulation................................ (6.0 cm) |                    |          |
|                               | Lime plaster (w<0.1 kg/m²h)................................. (0.5 cm) |                    |          |
| ROOF SYSTEM$^a$ (Gable Roof) | Clay Roof Tiles............................................ (1.4 cm) |                    |          |
|                               | Battens.................................................... (3.0 x 5.0 cm) |                    |          |
|                               | Air (gap) layer + Battens................................ (5.0 x 5.0 cm) |                    |          |
|                               | Waterproof membrane........................................ (0.2 cm) |                    |          |
|                               | OSB panels.................................................. (2.4 cm) | 0.21                |          |
|                               | XPS insulation + Rafter.................................... (16.0 cm) |                    |          |
|                               | Vapour barrier............................................... (0.1 cm) |                    |          |
|                               | Gypsum-cardboard panels................................... (1.2 cm) |                    |          |
|                               | Lime plaster................................................ (1.0 cm) | $U_{\text{max}} = 0.25$ |          |
| ROOF SYSTEM$^c$ (Gable Roof) | Prefabricated straw bale panels + LVL rafter................ (30.0 cm) | 0.14                |          |
|                               | „Smart“ vapour barrier..................................... (0.2 cm) |                    |          |
|                               | Cellulose fibre insulation + Battens....................... |                    |          |
|                               | ........................................................................... (6.0 cm) |                    |          |
|                               | Gypsum-cardboard panels................................... (1.2 cm) |                    |          |
|                               | Lime plaster.................................................. (1.0 cm) |                    |          |
| FLOOR SYSTEM$^a$ (Ground level) | Floor finish (wood)........................................... (2.0 cm) | 0.44                | $U_{\text{max}} = 0.40$                   |
|                               | Screed layer (cement)........................................ (5.0 cm) |                    |          |
|                               | XPS insulation............................................... (6.0 cm) |                    |          |
|                               | Damp proof membrane......................................... (0.2 cm) |                    |          |
|                               | Reinforced concrete slab................................... (15.0 cm) |                    |          |
|                               | Gravel........................................................... (30.0 cm) |                    |          |
| FLOOR SYSTEM$^c$ (Ground level) | Floor finish (wood)........................................... (2.0 cm) |                    |          |
|                               | Battens + Air (gap) layer.................................. (2.5 cm) |                    |          |
|                               | Prefabricated straw bale panels........................... (20.0 cm) |                    |          |
|                               | Battens + Air (gap) layer.................................. (2.5 cm) | 0.24                |          |
|                               | Vapour-permeable cellulose boards........................ (1.5 cm) |                    |          |
|                               | LVL beam (30 cm) + Air (gap) layer....................... (70.0 cm) |                    |          |

$^a$ & $^b$ Buildings demolished in the landslide; $^c$ with prefabricated straw bale panels; $^d$ Sd<0.2 m; $^e$ calculated using [17].

In straw bale structures, a chainsaw is sufficient to separate finishing layers from the straw, which is not the case with inorganic materials' bonding. The ever-growing data on the number and spectrum of
functions that this material possesses in derived facilities worldwide are encouraging indicators of the slow but evident change in public awareness. With further improvement of technologies and research of physical - technical properties, compressed straw and her products will be gradually but surely established on the scale of modern materials of the 21st century.

The key is to answer this question: Do we want to live with the materials that look bad before they start to behave like that, or with the materials that behave bad long before they show that visually?

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