CONSTRUCTION METHODS WITH STRAW AND THEIR POSSIBILITIES FOR A LOW-TECH AND SELF-BUILDABLE APPROACH

Thematic Research

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Abstract
There is need to redesign dwellings and layout of Reception and Identification Camps (RIC) to provides the refugees with sustainable, affordable and climate appropriate design of the dwellings, and to fosters economic activity and interdependence with its host country. This research goes into whether cereal crops together with its by-product straw as a building material can play a vital role in this redesign, by investigating its possibilities of using this material in order to create climate appropriate, affordable, low-tech, and self-buildable dwellings (and thus be applied in RIC). Straw bale houses are able to withstand Mediterranean climate, and its building physical properties match those of conventional building methods. The construction method of using straw bales in order to create a loadbearing wall has the potential to meet the criteria of climate appropriate, affordable, low-tech, and self-buildable dwellings.

Keywords: *climate appropriate, affordable, low-tech, self-buildable, straw bale construction, straw yield*

0.
INTRODUCTION

Problem statement

In Europe, Reception and Identification Camps (RIC), the dwellings and layout of the camp are in poor condition, leading to mental issues for refugees. Refugee camps and host-country would benefit of a redesign of the camps that not only provides the refugees with sustainable, affordable and climate appropriate design of the dwellings, but also fosters economic activity and interdependence with its host country. Interdependence being sharing of resources and services of refugee and host-country.

In the research on how to approach question, using straw as a building material as a possible solution came to light. A noteworthy aspect is, that it is a by-product of cereal crops used to make food. Because of this, the hypothesis is that by using the straw as a building material for the design of the shelters in a RIC has the following advantages.

- It can help refugees to be (economically) active by cultivating cereal crops (to be specified in the thematic research), by processing these crops into food, and the straw into buildings.
- The possible low-tech solution of building with straw means that refugees can be directly involved in the building process
- Has the insulating capacity to withstand Mediterranean climate
- The building process and cultivation of cereal crops and processing to food could benefit the local economy as well
- Another point of appeal is the possible low-costs of building material.

In other words, the hypothesis is that straw as a building material is more affordable than conventional building methods, and is capable of creating dwellings with sufficient insulation for Mediterranean climate. It is low-tech method of construction, meaning there is little to no need for heavy machinery like, cranes, excavators, compactors, concrete truck mixer, pile driving machines; machinery which requires professionals to handle. Lastly it should be self-buildable; laymen who have little knowledge of construction should be able to partake in the construction process. In order to test this hypothesis, knowledge has to be gained on straw as a building material, and understanding whether it can meet the criteria described above.

This leads to the following question:

"What are the possibilities of using straw as a building material in order to create climate appropriate, affordable, low-tech, and self-buildable dwellings?"

In order to answer this, the following sub-questions will be discussed:
- *What are the building physical properties of straw?*
- *What construction methods for building homes with straw do exist?*
- *What types of cereal crops are most suited in order to gather straw for the purpose of building?*
- *How much straw and cultivated land of cereal crops are required to meet the need for the aforementioned construction methods?*

Methods

Through literature review including books and journal articles on construction methods and on building physical properties of straw bale buildings the first and second sub-question will be answered.

For the first question, the data of the building physical properties of straw will be compared to the Greek building code, to see whether they meet the standard required for single storey residences. In this segment, affordability and potential for climate appropriate design of straw itself on Lesvos will be discussed.

For the second question the differences between the various types of construction methods will be researched. The focus will be on main construction methods; loadbearing straw bale wall, vs non-loadbearing straw bale wall. Within these methods, attention will be paid to the three elements which constitute the shell of a building, the roof, façade and foundation, and whether they are (as a method) affordable, climate appropriate to Lesvos, low-tech and self-buildable as defined.

The third question will be a short segment in the whole. It will result in a list of most suitable cereal crops. Literature reviews on most used straw for buildings and their properties and climate requirements for growing will be conducted.

After this, a quantification of the flow of straw will be made through analysing existing data on straw yield for the analysed, which is in kilogram (or kilotons) per land unit (hectare). Another part is calculating the amounts of straw needed to build different types of wall, the unit for this is usually kg/m^3. The result will ideally be an understanding on straw yield per type of straw per unit of cultivated land (example square metre) and how this amount of straw corresponds to the building of square metre of walls. Together with the previous findings, an understanding of how much cultivated land for how much wall for the different types of construction is developed.

1.
BUILDING PHYSICAL PROPERTIES AND BEST PRACTICES

Building with straw is nothing new, the first recorded straw bale building dates back to 1880s, (coinciding with the first recorded straw bale compressors) with the oldest known still standing and inhabitable straw bale building dating from the beginning of the 1900s. (Minke & Krick, 2020) The use of straw as a building material was pushed to the background due to the standardization in the building process of building materials like concrete. The start of the increase in popularity straw has now, dates to the early 1980s, due to renewed interest in ecological building and initiatives from self-builders. (Downton, 2012) Ecologically speaking, straw has several advantages. Straw uses carbon dioxide through photosynthesis during growth, so when straw is used as a building material instead of being burnt, it is an 'effective way of removing and storing excess carbon dioxide from the atmosphere'. (Walker, Thomson, & Maskell, 2020) What's more, straw does not need chemicals in order to be resistant to vermin. (Kubba, 2017) It has the potential to reduce usage of wood and concrete, as we will see in the discussion on construction methods.

Fire resistance

Straw can be sufficiently fire resistant to meet building code, making it in this regard a safe building material. When processed properly, that is.

For fire resistance, bales need to be properly compressed, with a minimum of 85 kg/m³. Through compression, not enough oxygen is present for the straw to ignite. Besides this, when exposed to fire, straw bales charrs. This charring of the outer layer is thought to inhibit further decomposition of the straw, just as is the case with timber charring. (Walker et al., 2020)

For loadbearing straw bale walls, a fire resistance rating of F30 (meaning, that the wall will be structural sound for at least 30 minutes in case of a fire) has been established in Germany, with a 30 to 50 millimetre thick clay render on each side. For non-loadbearing walls, the same fire rating has been established with a minimum of 10 millimetre thick render. (Minke & Krick, 2020) When a lime render is used with a thickness of 80 millimetre, the rating can go up to F90. (FASBA, 2019) It could be argued that an F30 rating is on the safe side of things. When compressed and finished with a earth render, non-loadbearing straw bale walls can last more than 135 exposed to temperatures of 1000 °C minutes without collapsing. Render on top of the straw bales can last up to 90 minutes before collapsing (Wall, Walker, Gross, White, & Mander, 2012), experiments have shown that a 45 millimetre thick render can half the temperature of the straw behind the render. (Walker et al., 2020) F30 meets the requirement for residential building code in Greece up to two storeys with a height of less than 5 metre for the highest floor level. (European Commission, 2017)

Insulation

The thermal conductivity of a straw bale is influenced by the direction stalks. If the general stalk direction is parallel to the outside, the thermal conductivity is around $\lambda = 0.050$ W/mK. If the stalks of the straw are placed perpendicular to the outside, the thermal conductivity is higher, around $\lambda = 0.080$ W/mK (Minke & Krick, 2020; Strobouw Nederland, 2020), resulting in less efficient use of the material when talking about insulation.

To get an idea if this is sufficient to build with, let us look at the following. Wit straw bale walls it is possible to meet the requirements for a residential passive house, if the walls are approximately 500 millimetres. To meet Dutch regulation on insulation for walls (R_c=4,7 m²K/W), a wall thickness of 4,7/0.05 = 0,24 m, or 240 millimetres would suffice (using formula $R = d/\lambda$). This means that the insulating properties are more than sufficient to meet the standards without the need for overly thick walls. Since on Lesvos, winters a less cold and summers a warmer, it can be argued that the insulating capacity of straw will suffice for the climate on the island.

In fact, depending on the climate, attention has to be paid to cooling, since the insulating properties of straw are described as above. (Downton, 2012)

Mould and rotting

Mould and rotting is not a problem, if the straw bales are kept properly dry and the detailing of the building allows for proper waterproofing. Steps have to be taken to ensure no condensation can happen inside the wall. Water pipes should not go inside the straw bales, as this can also cause condensation and in turn mould and rot. While avoiding thermal bridging is always important to ensure good insulation, for reasons of rot and mould, this is of extra importance in straw bale walls. Steel frames are therefore not recommended. What's more, it has to be ensured that the moisture content of straw bales is below 20%, (Cascone, Rapisarda, & Cascone, 2019) with some sources claiming below 18% or even below 15%. (Minke & Krick, 2020; Strobouw Nederland, 2020) When using jumbo bales (ca. 80 cm wide), insulation on the outside is required to prevent exterior of the wall to be colder than the interior, leading to condensation inside the bales.

Wall build up - vapour permeability, wall finishing, water resistance

Regardless of the construction method, there are some general rules regarding the make-up of the wall. If a wall is wider than the width of one bale, straw bale walls should always be laid in a running bond. (Walker et al., 2020)

Straw bale walls have to be vapour permeable to prevent any form of condensate, this has influence on the choice of type of finishing on the wall. For finishing interior walls, plastering is the simplest way. Earth render has great advantages since it regulate humidity, has great thermal mass regulating indoor temperature, and is cheap. For exterior walls, protection from driving rain and capillary action is needed to prevent straw from getting to moist. The easiest way of doing this is using boarding in front of a rendered surface. Another possibility is to use renders that are treated in a way to make them waterproof. Attention has to be paid that not of these treatments reduce the vapour permeability of the wall. There are several methods to use renders without boarding. Stabilised earth plasters are a possibility, adding mineral or synthetic or organic material. The easiest is however a lime render with added cement. Lime render with liquid manure will also result in a water resistant finish. The amount of roof overhang also plays into the integrity of the water resistance. (Minke & Krick, 2020)

In terms of being self-buildable, plastering is not difficult as much as it is time consuming. When having enough voluntary man-power, this should not be an issue and also keep the costs down. It is necessary to have supervisors around who have the technical skills to ensure proper application and quality control.

During construction

Even though compressed straw bales form no fire hazard, loose straw stalks easily catch on fire. It is therefore of essence to maintain a clean construction site. It is at all times necessary to prevent straw from getting wet, from storage, during construction, and after the construction is finished. The straw bale wall should have a clearance of 300 millimetre above the ground, to prevent capillary action and excessive moisture from splashing rain. (Strobouw Nederland, 2020)

Noise levels during construction with straw bale walls are much lower than when using conventional materials like concrete, requiring heavy machinery. According to Downton (2012), an architect having more than 15 years of experience with building with straw, this decrease in noise and therefore increase in ease of communication on the construction site, fosters a sense of community during construction.

Costs of straw bales

Since straw is a by-product of cereal crops, it is a cheap material. Compared to its conventional insulating counterparts. Minke et. al. (2020) notes that a 300 millimetre thick layer of straw, is 5 times cheaper than a cellulose fibre insulation, or 6.5 times cheaper than a 24 millimetre thick rock wool insulation. When the straw is used to bear the loads as well as insulating, it is an extremely efficient use of the material, since no added structural frame is needed. If the source of straw is local, the costs are even greater reduced due to minimal transport costs.

2.
CONSTRUCTION METHODS OF STRAW BALE BUILDINGS
In relation to costs, low-tech, and possibilities to self-build

There are two main construction methods with using straw bales as a building material for new buildings. The first one is the loadbearing straw bale wall, where the loads of the roof are being transmitted to the foundation directly through the bales in the wall. These walls have an insulating as well as a structural function. The second method is the non-loadbearing straw bale wall. In this method, the loads of the roof are transmitted through a frame construction, usually made of timber. The straw bales' main purpose with this method is insulating. Within these main methods there is a variety of ways on how to execute these methods, which will be on elaborated next, together with the construction processes. Depending on the country, the non-loadbearing method can make it easier to obtain building permits, since structural calculations can be done accurately due to the timber framing. However, the loadbearing method has been around for more than 100 years without any major know structural failure, and has been built with in countries like Denmark, France, Switzerland and Austria.

<u>Loadbearing straw bale walls</u>
Bale size

Since this is a very straightforward way of using straw bales in construction, there are not many variations. Within this construction method, the biggest differentiator is the size of the straw bales used for the walls; either big or small. While exact sizes of straw bales can vary due to lack of standardization, a straw bale is considered small when around the following size; 36 x 48 x 80cm. (Strobouw Nederland, 2020; Walker et al., 2020) Straw bales considered large tend to be around 80 x 80, with the length varying. (Minke & Krick, 2020) According to Minke & Krick (2020) big bales are preferred. Larger bales have a larger surface to distribute the roof loads and have a higher degree of compression, which results in lower deformation under load. However, other sources claim that small bales are also suitable. (Walker et al., 2020)

The choice for which size to use has to do with:

- the available space: thicker walls require more space
- climate: thicker walls provide better insulation, which can be necessary depending on climate
- possibility to prestress walls (larger bales are usually more compressed, needing less prestressing)

In terms of affordability, this is the most economical way of using straw, since a lot of wood is saved by excluding the need for a structural timber frame, and straw itself is relative to other insulating and structural building materials, cheaper. The cost for this methods lies in the applying the finish on the wall in terms of time, when earth or lime render is used, as discussed in chapter 1. However, with enough voluntary man-power, this can be neglected.

In terms of low-tech and self-buildable, this method fits the criteria. This method requires little trade skills for construction. Mainly manpower to execute basic tasks, like lifting the bales in place and applying the finishes. Most tasks can be executed with light machinery like drills and saws. Having supervisors on site who have experience in building with this method is all that is needed, especially when it comes to applying the finishes on the wall and detailing to ensue waterproofing and airtightness. No heavy machinery is needed, but can expedite the process. This method has an advantage that less pre-planning is needed and the whole building can be built relatively fast compared to other straw bale building construction methods.

Construction principles unique to loadbearing straw bale walls

Finishings/renders are an integral part of the structure, where tests show that lime renders are very strong. In loadbearing walls, they can absorb vertical loads as well, mitigating the need for cross bracings. This is for example allowed in the building code in California. (Cascone et al., 2019; Minke & Krick, 2020)

There are limitations in terms of roof design. It needs to make sure that load is uniform applied on all walls. This has consequences for (limiting) the possibilities of the roof design. Square and pyramid shape are the most preferred ones. Gable or saddle roofs won't work without any extra structural measures. Keeping lightweight is not necessary, but has obvious advantages. A ring on top of the wall is of essence for equal distribution of loads from the roof. This ring beam can also be used for prestressing. Loadbearing walls tend to shrink when heavy loads are applied the first time to the wall. To mitigate this, walls can be prestressed. Meaning, pressure can be applied to the wall until no shrinking of the wall is observed. This can either be done by letting the weight of the roof compress all the bales until no further shrinkage is observed. Another method is retensioning; over a course for at least three weeks, increase the tension of the tension straps, until no further shrinkage is observed, a method brought forth by Minke & Krick (2020) According to them, balls laid flat should be compressed by 14%, balls laid on edge by 10%.

To mitigate weather dependence, a temporary shelter can be built using tarp, or by putting the roof in place first, propping it up until the walls are ready to receive the load of the roof.
Minke & Krick show some promising low-tech solutions for foundations, using old car tyres with lean concrete, providing the foundation and splash zone in one.

Non-loadbearing straw bale walls

As mentioned, this method is characterized by the fact that the walls themselves do not transmit any loads from the roof to the foundation. A frame, usually made of timber to avoid condensation and/or thermal bridges, transmits these loads. Within this method, there are three main variations; prefab, infill and wrapping.

Using prefab straw bale walls is working on the same principles as prefabrication methods for other materials, for example concrete. Sections of wall are being created in the in a factory or workshop, to be then transported to the construction site for installation.

The infill method differs from this, in that the timber frame is create on site, and the straw bales are put in between the posts an beams.

Wrapping consists exactly of what the name suggests. Building a sturdy wall, again usually made of timber, which is then wrapped with straw bales.

Prefab

Prefab section of timber walls with straw infill have the same basic advantages as using, for example, concrete prefab wall segments. The construction time on site is relatively quick, tolerances can be tighter and quality control is easier. This method does require a lot of trade skill and some heavy machinery like a crane for lifting the wall segments into place. Trade skill is required since assembling the timber frame requires knowledge on wood construction. Pre-planning is also required. In other words, in terms of low-tech and self-buildability, this method is not suited. Compared to loadbearing walls, this method is less affordable since it requires more trade skill and material.
This method gives more freedom in terms of design than the loadbearing system. There are no specific limitations on roof shape, since this is basically a regular timber frame construction, with the only

difference being the use of straw as insulation and wall face. This also gives you more freedom on placements of openings in the façade.

Infill

For the construction of the timber frame on site, there is still the need for good craftsmanship, making this method less suitable for self-builders. However, staking the straw and applying finishing is the same as with the loadbearing method; it is not difficult, it mainly requires time and manpower. The difference in cost for this method as opposed to prefab method are difficult to make explicit. Trade skills are still required, however, the stacking of the wall could be done by volunteers. What can be said is that this method costs on average more money than the loadbearing one.
Just like the prefab method, infill gives you more freedom in terms of design than the loadbearing system in terms of openings and the roof. However, unlike with the prefab method, these walls have to be prestressed, just like the loadbearing walls. Openings are also achieved by a timber construction, with the loads being transmitted through this, not the straw bales. With this method, extra attention has to be paid to the placement of the posts in relation to the cladding, since plastering can take a lot of extra time when there are wooden posts in between sections of wall.

Wrapping

With wrapping, a solid wall is constructed, and the straw bales are placed in front of this wall. The same principles as with prefab and infill apply, as in, there are no limitations on roof shape or wall openings. It usually requires more timber than those methods, since the wall face is not just the straw bale, but a complete wall of wood. As is the case with other two methods, trade skill is required since assembling the timber frame and wall requires knowledge on wood construction. Pre-planning is also required. Also this method is not suited for low-tech or self-builders. Just as is the case with infill, the stacking of the bales can be done by laymen, however they need to be secured to the wooden wall, which requires some skill.

3.
TYPES OF CEREAL CROPS FOR STRAW

Straw is a by-product of cereal crops. They are the dry stalks of processed (threshed) grain, like wheat, rye and millet. Fibrous plants like flax, hemp, or rice also leave behind dry straw stalks.
According to Minke et. al. (2020), it is best to use straw bales from wheat, spelt and rye. These are more stable then barley and oats. However, Ashour & Wu (2011) claim that barley straw bale walls are a decent option to produce sustainable buildings. What's more, the research of Marques. et. al. (2020) into rice straw bale walls show that this is also a suitable candidate for making sustainable walls, with little difference to, for example, wheat. In his book about straw bale houses, Hollis (2005) argues that most types of straw should be fine, as long as the moisture content is low enough, as discussed previously.

From all of this, it can be argued that because of all of this, the best straw to use, is the one most local to where the buildings will be created. This will keep transport costs down and make best use of the sustainable nature of straw bale buildings. In combination with this argument for locality, the local climate should be taken into account for the possibilities of growing different types of crops.

According to the FAO, the Food and Agriculture Organization of the United Nations (2021), barley and wheat cereal crops which are most suitable for Mediterranean climate, the climate of Lesvos, Greece. In Greece, both barley and wheat are being cultivated, with the latter being cultivated the most.

4.
STRAW YIELD

The outcome of this chapter will be an insight into how much m² cultivated land is needed in order to produce a m² straw bale wall for loadbearing and non-loadbearing walls. This will be calculated for wheat, since these are the most commonly cultivated in Greece

Averages for straw yield are very difficult to come by. An average of 4-5 tonnes of straw per hectare seems to the average a lot of farmers go by (from discussions on forums), as also stated by the University of Kentucky (2013). These numbers will be used to get a general idea on these quantities. For further research, contacting farmers to get precise numbers on straw yield for different types of crops will be the next step. We shall take 4,5 tons of straw per hectare. This is 4500 kg per 10000 m².

<u>Amount of straw for 1 m² of wall - Non loadbearing</u>
For non-loadbearing straw bales, we will use the average of a density of 100 kg/m³.
The wall thickness for non-loadbearing walls are 0.5 m on average. This means that the volume for a wall of 1 m², is 0,5m³ (1m x 1m x 0,5m). This results in **50 kg** for a 1m² of wall with bales of a density of 100 kg/m³ (100 = kg/0,5 → kg = 0,5 x 100 = 50 kg)
For this amount, (10000 m² x 50 kg)/4500 kg = **111 m²** of cultivated land are required.
<u>Amount of straw for 1 m² of wall - loadbearing</u>
For loadbearing straw bales, we will use the average of a density of 110 kg/m³.
The wall thickness for non-loadbearing walls are 0.75 m on average. This means that the volume for a wall of 1 m², is 0,75m³ (1m x 1m x 0,75m). This results in **82,5 kg** for a 1m² of wall with bales of a density of 110 kg/m³ (110 = kg/0,75 → kg = 0,75 x 110 = 82,5 kg)
For this amount, (10000m² x 82,5kg)/4500kg = **183 m²** of cultivated land are required.

When the design for dwellings take more shape, these number can be converted to required land use for one entire dwelling.

5.
CONCLUSION

Straw bales have excellent building physical properties which make them suited for creating dwellings in different types of climate, including the climate on Lesvos, Greece. Fire resistance is not an issue. Attention has to be paid to moisture, since this is the weakest point of straw: Keeping the bales dry at all times is imperative to prevent rot or mould from forming.

We have seen that there are two main systems to build with straw bales: loadbearing and non-loadbearing straw bale wall. The option most suited to answer the question of affordable, low-tech and self-buildable possibilities with straw, the non-loadbearing method is the most appropriate. In terms of self-buildable, this method requires the least amount of trade skill and heavy machinery, and most amount of man power. That means, *if there are enough volunteers to help stack the bales and build the dwellings*, the dwelling can be erected relatively fast and cheap, since there is little heavy machinery required and not many workers which have to be paid.

The trade off when using loadbearing in terms of design possibilities is less control, stuck to certain roof shape and smaller openings. There are also upsides to this: the whole method is more ad-hoc, less pre-planning is required and there is a real possibility for owners (or users of the building) to be part not only of the planning, but also of the building process. A process in which sense of community is fostered through lower noise levels then on more conventional construction sites.

To summarize, with these criteria mentioned, it can be concluded that the loadbearing system shows great potential for self-buildable, low-tech and affordable construction, with sufficient insulation for the climate on Greece, using wheat or barley. The next step will be to put this to the test and see how far the designs of dwellings can be pushed and with it quantifying the amounts of straw and cultivated land using the numbers presented in this research.

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