A Full Performance Paper House

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Abstract

According to the UNHCR, in 2019 there were 70.8 million refugees worldwide. Due to war, catastrophes, and emergency situations a great demand for temporary accommodation has arisen within the last couple of years. The main requirements for these shelters are protection for the inhabitants, easy transportability, and quick construction. In addition, in terms of resource efficiency, the recyclability of the construction materials is of great importance. Paper materials have a high potential for this, due to their strong structure, cost-effective production, and optimised recycling processes.
The following paper presents a case study of a prototype for a temporary paper house that meets the static and technical requirements for a comfortable and hygienic living space by combining different paper materials.
The overall objective of this research was the constructive development of building elements made of paper materials, which meet the requirements for temporary residential use over a period of at least 3 years. The main advantages of using paper materials for this purpose are easy processing, cost-effective production, and a high probability for its sustainable disposal after usage. The main challenges of the material are fire protection and moisture protection, which affect the recyclability, as well as the gluing and joining techniques. An overview of possible solutions for these disadvantages and their applicability will be demonstrated and discussed.
The paper aims to emphasise that simplicity and performance do not need to be diametrically opposed. The envelope, which provides all the functions required of a modern building through its multi-layered structure, represents the performance of this project. Transportation, construction, and joining, on the other hand, were kept as simple as possible in order to make assembly possible even by unskilled workers and under very basic conditions.
The paper is divided into four sections. First, the technical and regulatory requirements for temporary emergency shelters, as well as the decisive characteristics of paper materials are described and analysed. In the second part, the architectural design and the construction typology are defined. The third part focusses on the elaboration and evaluation of building elements with regard to joining technologies, statics, building physics, and production technologies. Finally, the results of the prototype and their transferability are presented and discussed.

Keywords

Paper, construction, building with paper, prototype, emergency shelter, full performance paper house

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1 INTRODUCTION

In recent years, global crises triggered by natural disasters and wars have led to a steady increase in the number of refugees, now reaching 86.5 million people (UNHCR Global Report, 2019, p. 5). In refugee camps, tents are available on site for shelter, though they are largely unsuitable for a medium to long-term stay. The hygiene situation is also in need of improvement, as often only collective washing places and communal toilets are available (UNHCR Global Report, 2019, p. 207).

One solution to improve the quality of housing is emergency shelters made of paper materials. Paper has been an everyday material for centuries and is used for writing, hygiene applications, packaging, transport, and other purposes. Different types of paper have been developed for all these different purposes. Meanwhile, there are more than 3000 types of paper (Friedrich & Kappen, 2012, p. 4). Paper has the advantages that it is produced cheaply, quickly, and from renewable resources. It is globally available and has highly optimised recycling processes.

As early as the 1990s, Japanese architect Shigeru Ban built the first experimental buildings made of paper materials. These were mainly skeleton constructions, in which cardboard tubes were used for the struts (Latka, 2017, p. 176 ff.). In 2012, the first commercially available paper house, the Wikkelhouse, was introduced in the Netherlands. This project also arose from the intention to create cheap housing for emergency situations within a short time frame. The building consists of a frame construction, which is wrapped in layers of paper materials by a machine (Latka, 2017, p. 233 ff.). Within the framework of the interdisciplinary project BAMP! (**BA**uen **M**it **P**apier (Building with Paper)), several institutes of the TU Darmstadt have been engaged in fundamental research on the use of paper as a building material since 2017 (Kanli et al., 2019; Kiziltoprak et al., 2019).

A wide overview of the topic of building with paper is provided by Dr. Jerzy Latka's dissertation from 2017, which also contains guidelines for the design of emergency accommodation and some prototypes (Latka, 2017, p.293 ff.). Paper as a building material offers the potential to establish a light and cost-effective construction method for temporary buildings. Even after the end of the period of use, unnecessary waste can be avoided as far as possible due to the generally good recyclability of the material.

The following research describes temporary shelters produced from paper materials, which can be built quickly and provide a certain basic level of comfort for their inhabitants. The requirements that have to be fulfilled for emergency accommodation are outlines and an explanation as to how these requirements are met with regard to architecture and construction is given. In addition, the knowledge gained from the prototypes is described and an outlook for future research questions is formulated.

2 TECHNICAL AND REGULATORY REQUIREMENTS

In order to design a paper emergency shelter, it was first necessary to determine the technical and legal requirements for this and to bring them in harmony with the specific characteristics of paper as a material.

The basic research revealed that approximately 86.5 million people worldwide were affected by fleeing and forced displacement. The reasons for this are mainly to be found in disasters, wars, and political persecution. About half of them are classified as "internally displaced people," whose migration took place within their home countries and often ended in large camps. Another 43 million people have fled to neighbouring countries, or even further away, and need to be taken care of there (UNHCR Global Report, 2019, p. 5).

According to the length of stay in emergency accommodation, a distinction is made between 4 types of accommodation (Latka, 2017, p.308):

- Emergency shelter — as a place to stay for a few days
- Temporary shelter — as a place to stay for a several weeks
- Temporary housing — as a place to stay for a several months to years
- Permanent housing — as a place to stay for years

The need for low-cost and easy-to-erect structures is present in all phases of accommodation. For this purpose, a modular system is designed, whose configurations allow both short-term emergency accommodation and longer-term solutions. Another important criterion is that the developed systems can also be erected by unskilled workers on site. With regard to its properties, the paper house is basically subject to the same requirements as any residential building. These include weather and fire protection, a comfortable indoor climate and sufficient durability. In addition, by using suitable materials, the highest possible degree of recyclability at the end of its useful life should be ensured.

For the temporary accommodation of people in Darmstadt, for example, as a solution in the refugee crisis, the legal requirements for the construction of a building made of paper were examined and clarified in a classic building application procedure with the municipal building administration. In this case, the greatest hurdle is currently the lack of fire protection certificates for the materials used. The results of this enquiry are only applicable within the scope of the Building Regulations of Hessen, Germany, of 2018; in the case of construction in another state or province, the associated applicable regulations have to be applied.

As the decisive characteristics of paper materials are to be considered: Paper is an anisotropic material and can absorb more tensile forces in machine direction than orthogonal to the machine direction. By applying moisture, the hydrogen bonds that bind the cellulose fibres in the paper can be dissolved, thus reducing the mechanical properties by up to 80% (Niskanen et al., 2012: 10).

Due to the fact that they are based on cellulose, paper materials have a capillary-active effect, i.e. they are water-draining. For this reason, it is essential to design the construction of the emergency accommodation in such a way that moisture can diffuse out of the building component and does not precipitate as condensation in the construction. It is precisely these properties that make water ingress a danger to the construction, and which are, on the other hand, beneficial to its later recyclability. By dissolving the fibre bonds in the water bath, it is possible to break down paper materials into their components and give them back into the material cycle.

Paper materials have good thermal insulation properties. The thermal conductivity of paper materials is already comparable with conventional thermal insulation materials without any additional optimisation processes. Recycled cellulose is commercially available as insulation material using the blow-in or pour-in process.

In the event of fire, paper forms a carbon layer depending on its raw density and composition. Due to this carbon layer, paper materials with high raw density show a similar fire behaviour to wood-based materials (Bach, 2020). Sufficient fire protection can be achieved by over-dimensioning load-bearing paper components. By coating or impregnating the material it is also possible to further optimise the building material with regard to its fire behaviour. However, certifications and proof from building authorities still have to be provided.

The following research questions arise from these requirements:

- *What type of modular system enables the combination of all the mentioned types of accommodation?*
- *Which structure is the most suitable for the individual segments to meet the constructional requirements?*
- *How can the connection of the respective segments be solved?*
- *How does the construction of such a system perform in practice?*

3 ARCHITECTURAL DESIGN AND CONSTRUCTION TYPOLOGY

Regarding the architectural design, the emergency shelters reflect the archetype of a house, since the gabled roof is understood almost regardless of culture as a pictographic association of living. In order to match this design approach with the claim to modularity, this form was also applied to the module.

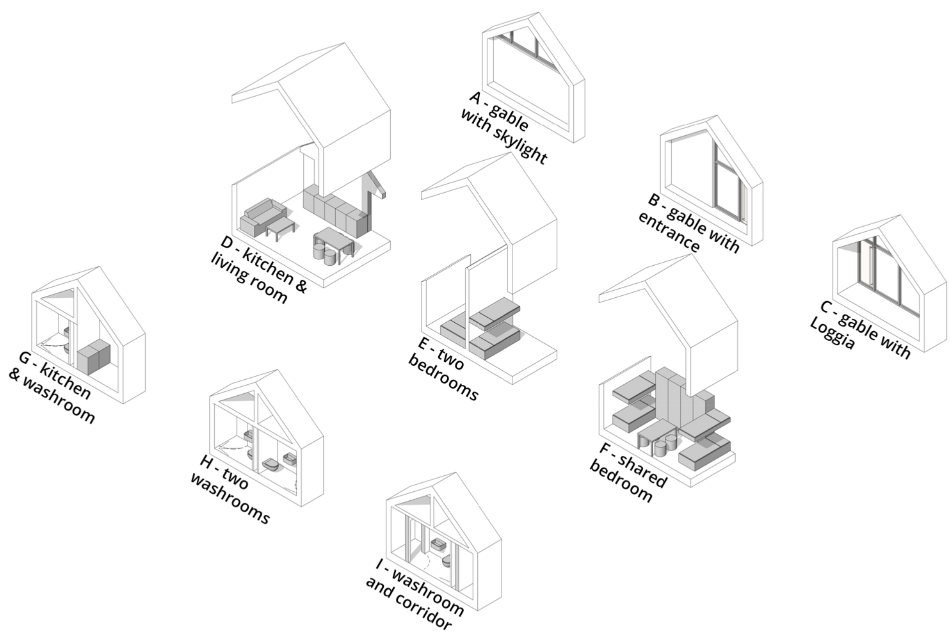

FIG. 1 Module typologies for different types of emergency accommodation depending on number of persons, duration of stay, and level of comfort

The modules are planned with a typical wooden grid dimension of 125 cm and can be combined with each other to form different house sizes. These modules (Fig.1) contain different living functions with reduced space requirements. There are end modules that can be used to close the front sides.

They also contain the windows and the entrance doors to the housing units.The developed system serves the typologies of accommodation (see Chapter 2 - Typologies of accommodation) in a modular way.

The developed systematics range from simple 4-person houses, which serve as emergency shelters for the first few days, to temporary shelters for a few weeks (Fig. 2), to temporary or even permanent housing for months or even years (Fig. 3). Common to all of them is the presence of sanitary units, which should guarantee the best possible hygiene with the greatest possible protection of privacy, especially in larger camp situations.

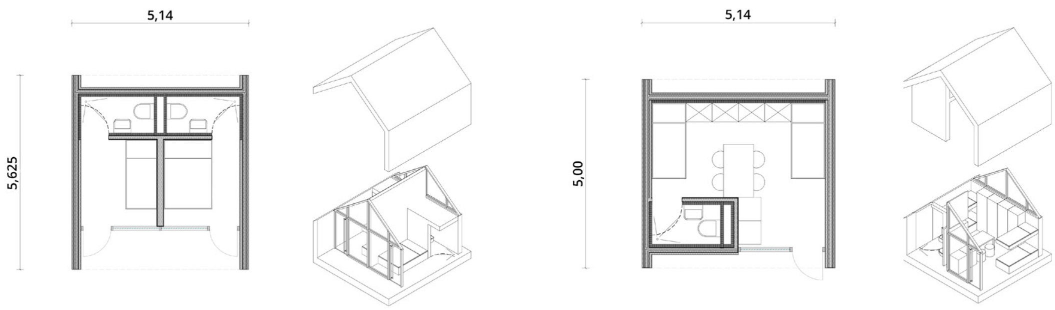

FIG. 2 [left] temporary shelter, [right] emergency shelter

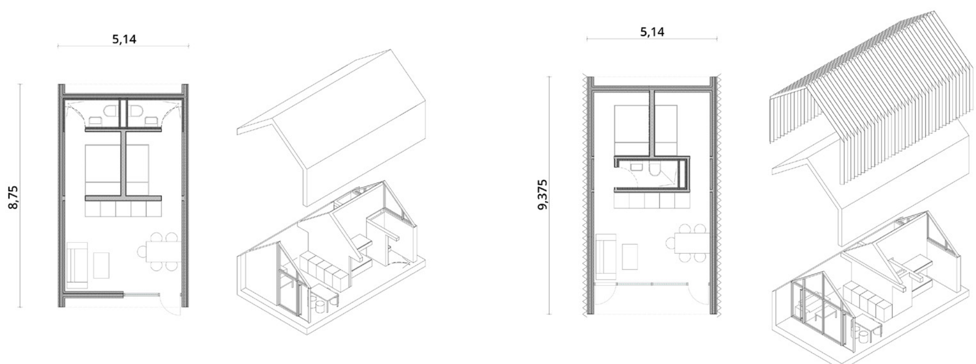

FIG. 3 [left] temporary housing, [right] permanent housing

To prove the constructive feasibility and the quick and easy erection, a demonstrator (Fig. 4) is produced. It has the dimensions of two frame modules and is intended to be used as a proof-of-concept by erecting it in an outdoor area of the TU Darmstadt after completion. Since assembly by unskilled workers is also one of the criteria used to develop the emergency accommodation, the speed at which this can take place will also be investigated.

By committing to a standardised module, it was possible to cover all of the scenarios mentioned in Chapter 2. The alignment of these modules provides sufficient flexibility in the longitudinal direction to meet the needs of long-term residents by providing additional rooms. The results of the design are certainly not to be regarded as exhaustive, since in the 125cm wide grid further spatial uses are conceivable. The question of the system to be used could thus be clarified by applying architectural design methodology.

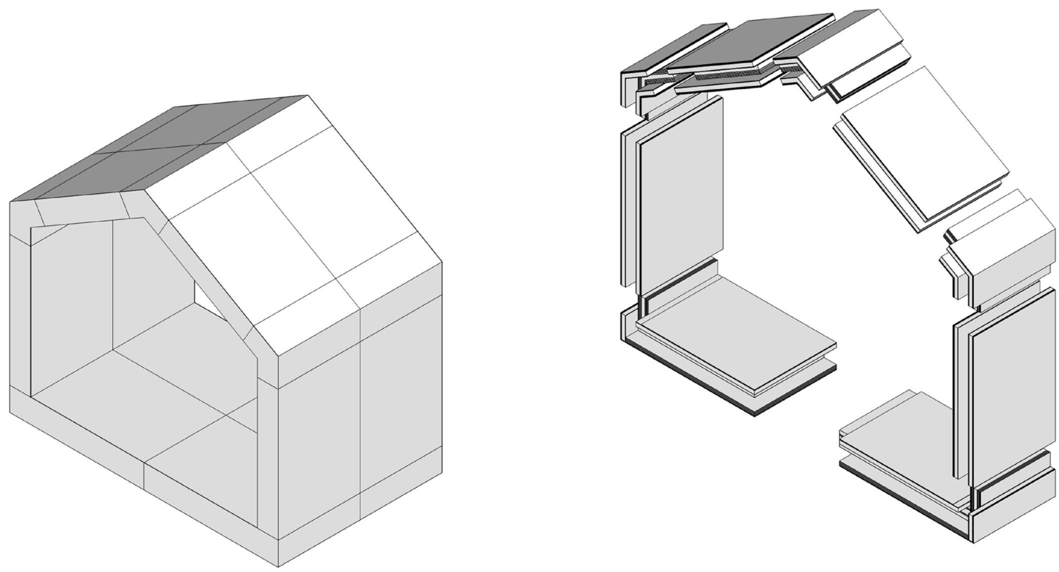

FIG. 4 Construction principle for the demonstrator of the paper emergency shelter

4 ELABORATION AND EVALUATION OF BUILDING ELEMENTS

The construction is a solid paper construction made of prefabricated segments. These are made up of multi-layer laminates with a thickness of 25-30cm, which are combined from cardboard with different specifications. Its production takes place under workshop conditions and the segments are only assembled to the respective frame modules on site. It is planned to equip the emergency shelters on site with a prefabricated wet room containing all the necessary building services installations, which means that piping in the paper construction is not required. Also, the installation of the window and door elements is scheduled only after the construction of the raw paper structure.

The layer structure of the outer walls, which also includes the roof, differs significantly from the layer structure of the floor segments, which is due to the different influences that the respective components are exposed to (Fig. 5). These influences decisively determine the selection and arrangement of the respective layers. The majority of the structure, in terms of the volume used, is made of corrugated cardboard, whose small-cell structure has a good insulating effect.

The layer structure of the wall segments can be divided into 3 areas, the inner and outer protective layer and the core layer in between. While the protective layers protect the structure from environmental influences, the core layer serves primarily to ensure the stability of the structure and is the only one used for the static calculations. It consists of several layers of corrugated and solid board, as well as a core of honeycomb board. The protective layers, which are symmetrically structured, also consist mainly of corrugated cardboard and are covered with phosphorus-impregnated solid cardboard, which has been approved for class B2 fire protection. In the construction of the floor segments, the bending stiffness of the building element and its resistance to rising damp are of particular importance. In contrast to the use of corrugated board, as in the case of the walls, honeycomb board makes up the largest part of the volume of the floor segments. Their cell structure, which is orthogonal to the segment direction, ensures a high degree of compressive rigidity in the thickness direction of the board, whereby the spacing of the cover layers, which is given by the core, ensures a high degree of flexural rigidity and contributes to the insulating effect of the component. Since no fire protection requirements are placed on the base slab, no B2-boards are used at this point. The focus is on the prevention of moisture damage, which is prevented with the help of a special water-repellent cardboard. This is also done on the inside and outside of the respective segments.

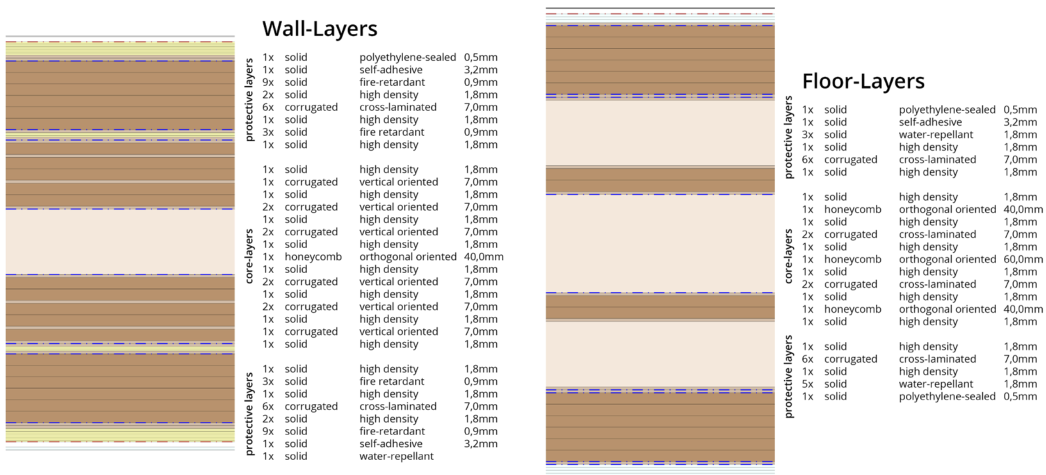

FIG. 5 Layer structure of the wall and floor segments

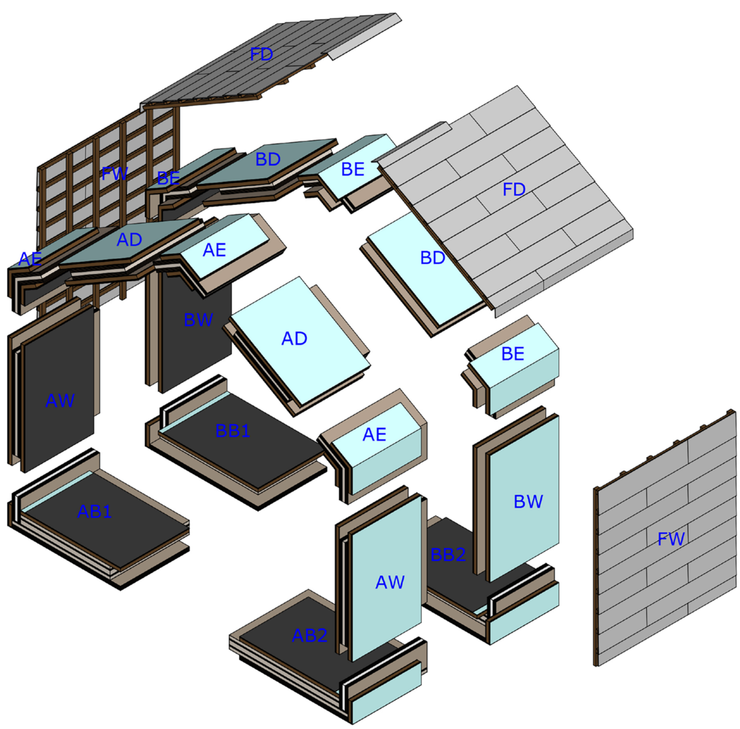

FIG. 6 Exploded view of the demonstrator

As a further protective measure against water, it is also planned to wrap the segments - regardless of their type – in an outer layer of polyethylene-sealed cardboard, also known as beverage packaging. The rain protection thus created is supplemented by a curtain-type ventilated façade made of shingles, which are also made of polyethylene-sealed cardboard (Fig. 6). In this way, an effective rain protection is guaranteed, because even in rainy weather conditions no large amount of water can reach the segments and with subsequent exposure to sunlight the small amount of water that has entered can evaporate again in the space between the segments. The shingles also offer the possibility of replacing single parts without much effort in case of damage.

A challenge in the production process of the modules is the joining by laminating of the individual sheets measuring approx. 1.25 x 2.50 m. Coating the surface with water-based glue leads to a permanent convex deformation of the freshly glued segments, which makes them unusable for further processing. Various attempts to counteract this effect by means of a joining process under pressure, for example with steel weights or wooden planks, failed.

Sufficient pressure has only been achieved with a vacuum pressing process. In this process, an elastic plastic bag is filled with the workpieces, sealed, and then the air is extracted using a vacuum pump. With this process, a surface pressure of up to 100 kN/m^2 can be generated, assuming an ambient pressure of 1 bar and complete evacuation of the plastic bag. Due to the prevalent workshop conditions, a complete evacuation was not achieved, which is why a residual pressure of about 0.3 bar remained in the vacuum bag during production. A surface pressure of approx. 70 kN/m^2 can therefore be assumed. Since the wood glue used initially hardens in the air, it was necessary to find an adhesive that would ensure hardening even under exclusion of air. Two-component adhesives and a few one-component solutions are particularly suitable for this purpose. For the production of the first prototype, a two-component epoxy resin with a processing time of 60 minutes was used, whereby a stable and flat bonding of the layers could be achieved. A disadvantage was that the adhesive had to be applied manually and the laminates had to remain in a vacuum for about 12 hours until the adhesive had completely set. As the epoxy resin was no longer available for the scheduled construction of the demonstrator, a naphtha-based product was found as an alternative which, thanks to its processability by means of spray guns and a hardening time of approximately 30 minutes, allows a more effective production.

The pre-produced segments are joined together using a tongue and groove system (Fig. 6). Here, the core layer takes over the function of the tongue, while the protective layers form the groove. This is ensured by shifting the middle layer by 15cm in both vertical and horizontal alignment. In order to guarantee the sealing at the connections between the individual segments, it is also necessary to fill the grooves with expanding foam sealing tape. In accordance with the hygric requirements for exterior components, it must be ensured that the construction is more impermeable to water vapour diffusion on the room side than to the exterior surface, so that possible water vapour diffusion out of the component is guaranteed.

In order to design the components, it was necessary to match the structural requirements for each component (roof, wall, floor) and the material properties of industrially available paper types. As a result, the functions were prioritised and the paperboards were "sorted" from inside to outside to form a component according to their properties. The tongue and groove connection made it possible to arrange component joints offset from each other and thus minimise weak points.
After several tests had determined a suitable adhesive for the laminates, the production of large-format prototypes began.

5 RESULT OF THE PROTOTYPES AND THEIR TRANSFERABILITY

Within the scope of this research, a prototype consisting of two wall segments and a demonstrator consisting of two module frames were produced. In addition, a large number of smaller test specimens were produced to identify the material properties and suitable joining techniques.

The following results were achieved:

- A combination of honeycomb board with a solid board lamination shows high bending resistance and is well suited for the construction of the floor structure. In addition, the high bending resistance is also an advantage for the wall module, as it can counteract buckling.

- Paper materials have good insulating properties and, unlike most other insulating materials, are able to absorb loads. However, this is highly dependent on the structure of the respective semi-finished products. If corrugated board, for example, is aligned vertically, a better load-bearing effect can be achieved than with a horizontal arrangement due to the stiffness of the webs contained in it. However, the vertical arrangement is at the expense of fire protection, as the vertical ducts lead to a chimney effect in the component in the event of a fire.

- The assembly of the components using the tongue and groove system demands additional connecting elements. These should on the one hand counteract the displacement of the elements along the joint and on the other hand prevent the segments from being pulled apart. For this application, connector elements can be used, as they are common in kitchen construction. For this purpose, however, it is necessary to equip the protective layers with a seam of squared wood, since paper materials deform when they are tightened due to their low edge crush resistance.

FIG. 7 The first prototype

Based on the results of these preliminary tests, a first prototype consisting of two wall segments was produced. This prototype was used to verify and demonstrate the assumptions of the preliminary tests as well as the manufacturing technology at a scale of 1:1 (Fig.7). One of the most important parameters to be considered for the production is the enormous amount of time required, since with the exception of the final trimming on the CNC milling machine, all steps for the production of the prototype are done manually.

After the successful production of the prototype, minor adjustments were made to the layer structure and the production process was optimised (Fig. 8). Since a large part of the manufacturing steps are still carried out by hand, the aim was to produce many laminates of the same type in a first step, which are then assembled into segments in the subsequent processes. A detailed assembly plan was also drawn up to enable a structured manufacturing process.

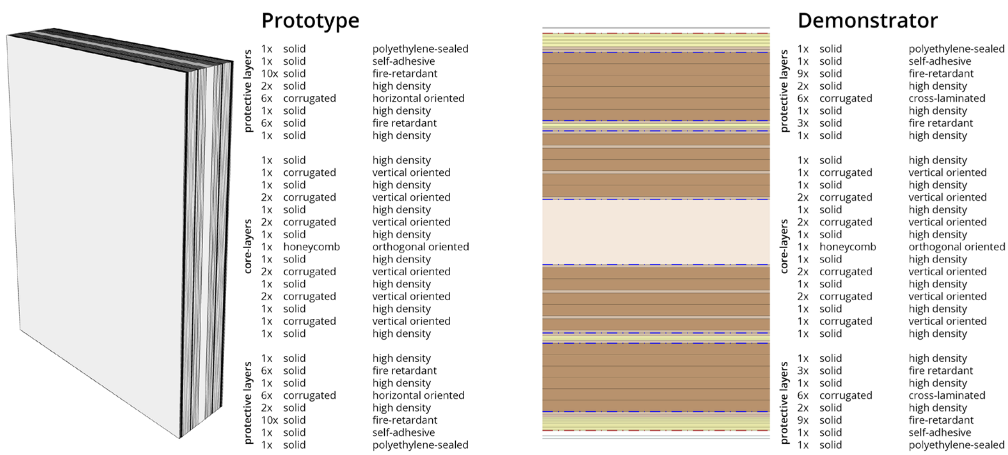

FIG. 8 Comparison of the wall-layers in prototype and demonstrator

Production of the final demonstrator began at the end of July and was completed in mid-September. A total of 18 segments were produced, which were then to be joined together to form two frame modules. In order to make the production of the demonstrator as efficient as possible, a detailed assembly plan was prepared. According to this plan, semi-finished products were initially manufactured, the layer structure of which is repeated in the building. In the next step, these semi-finished products were joined to form the respective layers (core layer and protective layers) of the building elements. These individual parts were trimmed with the help of a CNC milling machine. In the case of the protective layers, the anchor holes for the connectors were also set using the milling machine. These elements were finally assembled to form the floor, wall, roof, and corner segments.

Before the demonstrator was erected, a gravel surface was laid as a substructure and compressed. This serves to ensure the seepage of water and to avoid movements in the subsoil caused by ground frost. Because of the rainy weather, the construction process was carried out under a protective tent. The construction was expected to be sufficiently watertight after the shingle façade had been applied. The construction of the approximately 3.50 x 2.50 x 3.25m sized demonstrator took place within three days and required a team of seven employees.

A layer of polyethylene-impregnated paper was spread over the gravel substructure to protect the components from sharp stones from the ground. Subsequently, an aluminium-sealed vapour barrier membrane was laid on top of this layer, which was later to protect the demonstrator from rising moisture. After laying the floor slabs, the walls were inserted, and the elements were tightened with the connectors. The aluminium-sealed vapour barrier was installed approx. 50cm above the ground at the building elements to serve as a plinth seal.

FIG. 9 Floor and wall modules. Assembly of the roof in the background

FIG. 10 Lifting the roof onto the construction

The assembly of the roof had to take place on the ground, because an overhead assembly of the up to 75kg heavy elements would not have been possible. Afterwards, the roof was lifted with the help of a fork-lift and lowered into the existing construction.

After the supporting structure had been erected, the “expansion” could begin the following day. On the inside, a protective layer of polyethylene-impregnated paper, which was attached to double-sided adhesive solid cardboard, was mounted. On the outside, wooden battens and counter battens were installed to ventilate the façade. The façade shingles made out of polyethylene coated paper were fixed to these battens as the outer protection layer.

The open sides of the gables were closed by a construction of extruded polystyrene sheets, after the front sides of the walls were also protected with a layer of polyethylene-impregnated paper. The U-value of the gable walls corresponds to the U-value of the paper construction. For this reason, a realistic indoor climate can be created to enable further testing and monitoring.

FIG. 11 The finished demonstrator

The demonstrator has been set up at the Lichtwiese campus of the TU Darmstadt. On site, it is to be exposed to real environmental conditions for 3 years in order to be able to make further statements about the usability of the material and the construction method.

During the fabrication and construction of the demonstrator, it was observed that:

- Manual gluing of the elements is very time-consuming and complicates the use of conventional adhesives used in the paper industry, since they were developed for machine applications.
- Trimming the segments on the CNC milling machine has only been possible for planar elements. The six edge-segments had to be cut out manually. Especially regarding the holes for the joints this was a very time-consuming task.

- The individual segments turned out much heavier than expected (see Table 1), which required four or more workers to put them into place. In future, the element weight should not exceed 50kg.

TABLE 1 Weight of the segments

DESCRIPTION		WEIGHT	QUANTITY
AB1	Floor tongue/groove	89,0 kg	1 pc.
AB2	Florr tongue/tongue	95,0 kg	1 pc
AW	Wall tongue	101,1 kg	2 pc.
AD	Roof tongue	74,5 kg	2 pc.
AE	Edge tongue	51,4 kg	3 pc.
BB1	Floor groove/groove	77,0 kg	1 pc.
BB2	Floor groove/tongue	82,0 kg	1 pc.
BW	Wall groove	93,5 kg	2 pc.
BD	Roof groove	68,5 kg	2 pc.
BE	Edge groove	46,0 kg	3 pc.
FW+FD	Shingles	105,0 kg	all
total		1.415,4 kg	

In summary, it can be said that the construction of the demonstrator required an unexpectedly large number of volunteers due to the high segment weights. However, with the exception of the forklift, the assembly was able to be carried out with simple hand tools. About 1/3 of the construction team consisted of employees who had already carried out the prefabrication of the segments. Due to the simplicity of the system the construction method was quickly explained to the remaining 2/3 of the workers.

6 CONCLUSION AND OUTLOOK

The developed system meets the essential requirements for temporary accommodation. With the construction of the demonstrator as proof of concept, it has been proven that the production of segment components from paper materials is possible and feasible. The assumptions made with regard to the durability of the construction will only be further investigated in the course of the demonstrator's three-year service life.

The knowledge gained during the design and manufacture of the demonstrator can be used as the basis for further solid paper constructions. Results on the durability of the construction under real environmental conditions can only be researched in situ.

In the medium term the construction of a habitable prototype is imaginable. The developed module variants by no means exhaustively reflect all possibilities in which the buildings can be used. Other floor plans and application scenarios are conceivable, such as the further development of the segment system into a kind of construction kit for paper houses.

A more in-depth scientific investigation is required, especially with regard to fire protection and adhesive technology. Since there is no available information on the fire behaviour of the construction method used, it is essential to research this before constructing an habitable building. With regard to the bonding technology, it is first necessary to investigate what a more suitable adhesive could look like. The epoxy or naphtha-based adhesives used in the tests prevent the building from being recycled at the end of its lifespan and should, from an ecological point of view, urgently be replaced. After researching a suitable adhesive, the question of what the industrial production of the segments could look like has to be answered. Gluing and subsequent pressing by hand cannot be assumed to be cost-effective and only cutting the segments by means of a CNC milling machine appears to be efficient. Once these questions have been clarified, it would be imaginable to produce the system in larger quantities and ship it to places where temporary accommodation is urgently needed as part of crisis and development aid.

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