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Digital twins of wooden shingle envelopes

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Abstract

Wooden shingles have long been used as a vernacular roofing technique in many well-wooded areas. Despite the fact that shingles, as local raw materials, are low in embodied energy, nowadays they are not much used in construction, as the specific craft knowledge for building shingle roofs and facades has not been well-documented. Consequently, it is now becoming more difficult to find a new generation of skilled workers who can perform this task. As a result, this type of architecture is gradually disappearing. This research aims to provide a technical approach for digitization and generation of an as-built three-dimensional (3D) reconstruction of wooden shingle envelopes. Towards this aim, digital twins of wooden shingle envelopes are generated based on step-by-step real-time 3D scanning of shingles and point-cloud processing of the obtained scans, while they are placed by craftspeople. Two experiments on two different types of wooden shingles are conducted to validate the proposed method, and a precise digital model of this valuable type of vernacular architecture is produced. Furthermore, the exact geometrical configuration, assembly rules, installation patterns, and technical details of the construction process are documented and explained in detail. This work concludes with potential future research directions including design automation and optimization of wooden shingle envelopes which could help the industry re-introduce the use of local raw wood in contemporary architectural constructions, and revive this cultural and artisanal heritage.

Keywords: wooden shingles, bio-based local raw material, digital twins, point-cloud processing, vernacular architecture, sustainable architecture

1. Introduction

Emissions of carbon dioxide and other greenhouse gases continue to rise rapidly [1], with a considerable amount coming primarily from the building and construction sector due to the manufacture of building materials and products such as steel, cement, and glass [2]. Additionally, the dramatic growth of the world population will require significant construction efforts which compel the building industry to implement more sustainable materials. Among all construction materials, wood as a natural material for construction purposes is in a highly advantageous position and has recently been promoted to the center of interest [3]. However, engineering wood for the production of timber panels and beams consumes a large amount of energy and requires unsustainable processing and modification techniques. Additionally, if treated with chemical substances, it will eventually increase the carbon footprint, and consequently, reduce the inherent sustainability of raw wood [4]. Indeed, raw wood as a local material is low in embodied energy and has been widely used in traditional and vernacular constructions, and has become part of the cultural heritage of many well-wooded areas. Vernacular architecture with local raw wood has always relied on the technique [5], and expertise of craftspeople. Regrettably, this knowledge of craftspeople for these kinds of vernacular constructions has been passed down from generation to generation only practically, yet has not been well-documented and archived scientifically in terms of technical details, geometrical configurations, and construction rules. As a result, many of these worthwhile traditional building systems are disappearing, and industries mainly tend not to use local raw wood due to labour shortages and construction difficulties with such irregular unprocessed material. Even in rare cases where these traditional building systems are implemented in contemporary constructions, they are of lower caliber with a lack of attention to the culture, context, and building performances in response to the environment.

Wooden shingles are one of these sustainable vernacular building materials and were widely used by expert craftspeople to cover building roofs and facades. This roofing technique greatly depends on craft knowledge and nowadays only a limited number of artisans know this technique. Subsequently, wooden shingle envelopes have remained unknown to many contemporary architects and have been being replaced with unsustainable materials such as metal or cement, even in areas where local wood resources are abundant (Figure1). This is mainly due to a lack of proper documentation and reliable 2D and 3D drawings to guide non-specialized builders to use this type of material.

The emergence of the "digital twin" concept in the fields of manufacturing, and production [6], along with advances in the field of computational design and computer vision has assisted the progress of digitization of local building systems and cultural heritages [7] to make thorough documentation of them. Digital twins are defined as three-dimensional virtual models of a system [8], which indicate the physical characteristics and functional attributes of that system. This type of information from the buildings can be obtained by real-time monitoring of the construction process using advanced sensing technologies such as laser scanning (LIDAR) and photogrammetry [9], which can provide useful data for architects, engineers, and builders. The obtained data from the sensors are processed using computer vision algorithms and libraries such as PCL [10], Open3D [11], CGAL [12], and Cilantro [13], as cutting-edge libraries that provide comprehensive functions to post-process the aforementioned data for digitization of the systems. Digital twins for construction are highly beneficial not only for the automated data acquisition from construction sites and supply chains, but also for surveying and virtual reconstruction of archaeological sites [14, 15], and acquisition of as-built geometry and documentation of traditional building systems [7]. However, the current state of the art in digital surveying of traditional buildings mostly centers on the protection, maintenance, and preservation of cultural heritages, without providing much information on technical details of the step-by-step construction procedure, assembly sequences, and material properties, with no guiding principles or plans.

In this paper, we present an approach for the digitization of traditional wooden shingle envelopes for two types of shingles, known as Bardeaux and Tavillons, which are used as roof and facade tiles in well-wooded areas. Our methodology contains a step-by-step as-built three-dimensional reconstruction of shingles, based on obtained point clouds from a 3D scanner. One scan is taken for each element during the assembly process, following that, the point cloud is post-processed by our algorithm, and the three-dimensional model of the element is retrieved. Two prototypes are built by expert craftspeople to validate the proposed methodology. Subsequently, the proposed approach enables us to make the digital twin of shingle envelopes, document and archive all the details for the assembly sequence, installation patterns, material properties, horizontal and vertical overlaps, size of elements for each row of shingles, and the quantity and position of nails for fastening the shingles. The outcomes could guide builders to use this type of natural raw material in contemporary architectural constructions, respecting traditional rules.

To the best of our knowledge, this is the first time a digital twin of wooden shingle envelopes has been developed in accordance with craft knowledge and traditional standards.

2. Related works

In the past few years, a number of projects in the field of architecture and engineering have attempted to make digital twins of various historical buildings such as bridges, churches, theaters, etc., with the help of 3D scanning and photogrammetry techniques. Projects and research of this type have assisted the progress of prediction of damages, preservation, and restoration of monuments and archaeological sites. Bilis et al. [16] made thorough documentation and conducted a graphic restoration study of the ancient theatre of Nikopolis, with the aid of 3D scanning and image-based 3D reconstruction. The study on the object dimensional imprinting of the Byzantine church of the holy apostles in Thessaloniki by Katsoulis et al. [17] provides the data collection of the geometric information, such as the shape, the size and the location of the monument. “Cyclopean Cannibalism”, a traditional masonry technique, was translated into a contemporary digital procedure by Clifford et al. [18], through scanning and virtual algorithms. Betrocci et al. [15] also presented a digital survey for the archaeological analysis and enhancement of Gropina site, by integrating data from laser scanning and photogrammetric instruments. In addition to the aforementioned projects for the digitization of cultural properties, the digital twin technique has also gained increased popularity in the domain of on-site construction, for automating building processes [19], autonomous navigation, object detection, real-time robotic assembly [20, 21, 22], and also the autonomous robotic fabrication of raw wood [23]. However, there is no proof of concept on the digitization of traditional wooden shingles, and this type of architecture is investigated in this article.

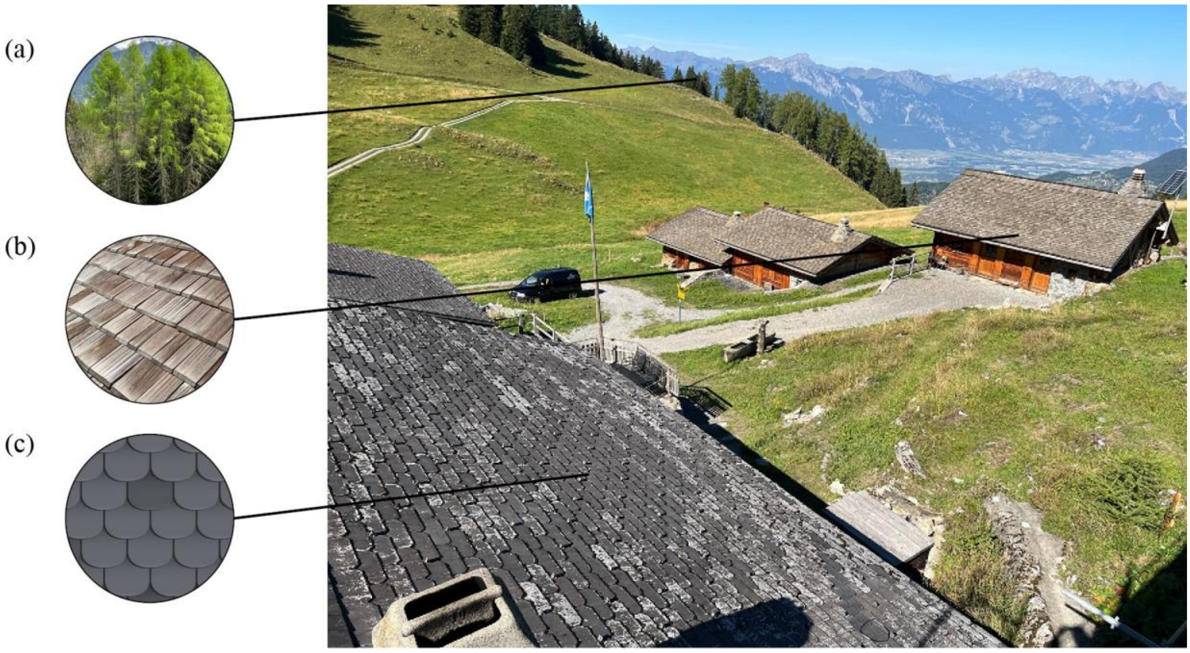

Figure 1. Implementation of unsustainable materials such as metal shingles in the construction of contemporary buildings, in areas where there are abundant wood resources that were traditionally used by local people in the past to construct age-old wooden shingle roofs: (a) Available material resources, such as larch trees, for wooden shingles, (b) Age-old wooden shingle roofs from 25 years ago constructed by local craftspeople and (c) a contemporary metal shingle roof built by present-day industries [Gryon, Switzerland].

3. Age-old wooden shingle envelopes

In this section, some general information is provided on the material characteristics and assembly rules of the historical wooden shingle envelopes according to some ancient references.

Shingles have long been used as a vernacular roofing technique in well-wooded areas. Attentively and dexterously done, shingles are superior to many other roofing methods in terms of durability, sustainability, exquisiteness, and monumentality [24]. The specific fabrication process of the material, makes the roofs and facades watertight and highly resistant against weather-induced decay, without using any chemical coatings [25]. Historically, shingled roofs were of immensely high caliber and were built by eminently expert craftspeople. There are two types of wooden shingles, known as tavillons and bardeaux in French. The key differences that distinguish these two types of wood are mainly the overlapping method and material resources, which will be explained in the following.

The thin nature of the shingle, its fabrication process, and its exposure to rain, snow, and sun necessitate high-quality wood. An ideal tree for this application should be straight, and must not be twisted. Additionally, it has to be mature and fine textured, without too many knots, and free from rot and blue stain fungi, with a large proportion of heartwood in relation to sapwood. Trees for this application should not be cut during spring or summer but in winter as it ensures high-quality wood. Tree felling is also bound to the phase of the moon. Thus, felling has to occur when there is a new moon, as it would make the timber more resistant to rot and to the depredations of insects. Trees should be barked immediately after felling, and definitely before spring to avoid the risk of rot and damage by insects. After bark removal, the trunks are sawn into log sections with the desired length, known as bolts [24, 26]. Afterward, each bolt is split in quarters from which sapwood is removed, all of which then is chamfered at one corner to avoid over-thickness during installation [24]. Following that, they would be split into rough shingles with a wedge and mallet [24, 27]. Tavillons are left submerged in the water to make them flexible for assembly, as they are naturally quite brittle when dried. Shingles are quite thin (0.7-1.9 cm), relatively narrow (7.6-20 cm), and with varying lengths (35-90 cm). The final products are always irregular with disparate geometry and size, and bumpy surfaces. The laying process is conducted by a series of rules conveyed by oral transmission and collaborative practice, without any execution drawings or technical documentation. A specific frame has to be built as the structure underneath, on which shingles are laid and nailed. The main constraint for the sub-structure is the slope which should not be less than 27◦, due to water tightness issues. What should be taken into consideration, first and foremost, is the consistency of the rows of shingles. Tavillons are placed over the previous one laterally with a side overlap corresponding to 1/3 of their width, this leads to three thicknesses per row. Each row vertically overlaps the previous one so that only 1/4 of the tavillon length would remain exposed, this ensures 12 thicknesses of the shingles. Mechanical fasteners are used for connecting tavillons, at least one nail is used per two tavillons. Some craftspeople use a different method, in such a way that instead of placing tavillons one by one, they place the tavillons in pairs and fasten them with one nail. On the other hand, bardeaux are placed beside each other with no horizontal overlapping. However, it is important to stagger each bardeaux by a minimum of 30 mm to avoid a seam alignment and a direct path for water leakage and thus ensure water tightness. Additionally, leaving a small space (3-12 mm) between two neighboring bardeaux is necessary for free swelling, due to the extreme variations of temperature and humidity they undergo. The same vertical overlapping as explained for tavillons is considered for bardeaux as well [26].

4. Digitization of wooden shingle envelopes

4.1 Methodology

In this section, a technical approach is presented for automating the as-built three-dimensional (3D) reconstruction of the wooden shingle envelopes in real-time based on point cloud processing. In this work, the already developed functions for point cloud processing from three main libraries including Open3D [11], CGAL [12], and Cilantro [13] were used to develop the digital twin. Furthermore, other functions were also developed by the authors. The main objective of the proposed approach is to achieve a reliable CAD model of the vernacular shingle envelopes by which we can detail all the specifications of shingled roofs and facades. As mentioned in the previous section, the shingle's geometry is uncertain, and each of them is of a different size and curvature, so the generation of CAD models cannot be carried out manually in CAD software such as Rhinoceros, or AutoCAD. Moreover, as shingles are laid over each other with horizontal and vertical overlaps and cover one another, it is not feasible to obtain an accurate 3D model of the roofs by 3D scanning of existing buildings with the conventional digital twin generation methods (see Section 2). Figure 2 shows a 3D model of an existing shingled roof covered with tavillons, generated by 3D scanning of the building using a Faro Focus 3D scanner, which was conducted as the first step for this research [28]. This 3D model could only provide some general information about the roof such as the size, the minimum required slope for the roof, and also a general overview of shingles, without any specific details on the laying sequence and installation patterns. Therefore, in order to generate an accurate and complete 3D reconstruction of these envelopes, an approach is presented to scan and digitize the shingles during the assembly one by one in order to extract the individual 3D models of each of them. Subsequently, an experiment is set up as shown in Figure 3-a. To detect the in-progress shingles and the sub-structure, a Faro Focus 3D scanner is mounted statically on top of the workspace to provide the 3D scans. The scanner is connected online via computer, in order to transfer the captured point clouds in real-time [29]. A sub-structure, composed of rafters (known as contre-lattage in French) with an 800*600 mm section and battens (known as Lattage in French) with a 27*100 mm section (the first row of battens has to be of a 27*160 mm section) and 100 mm spacing, which are installed on rafters, is fixed on the worktable with four targets at the corners. One scan is taken per shingle right after it is positioned by a craftsperson (Figure 3-b), and then it is imported into our C++ project to be post-processed in order to extract only the detached 3d point cloud of the last assembled shingle (Figure 4). The surrounding environment is filtered out (Figure 4-a) and the points belonging to the last assembled shingle are clustered (Figure 4-b). This process is repeated for all the shingles until the full 3D model of the prototype is obtained. The result could elucidate all assembly techniques which are performed by craftspeople.

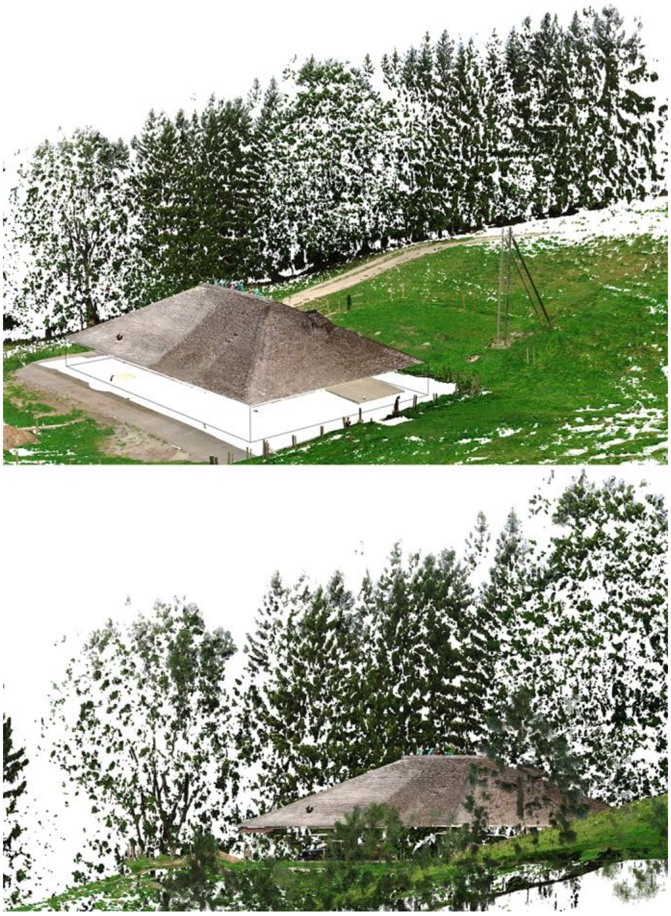

Figure 2. Three-dimensional model of an existing age-old wooden shingle roof in Rossiniére, Switzerland, 2022.

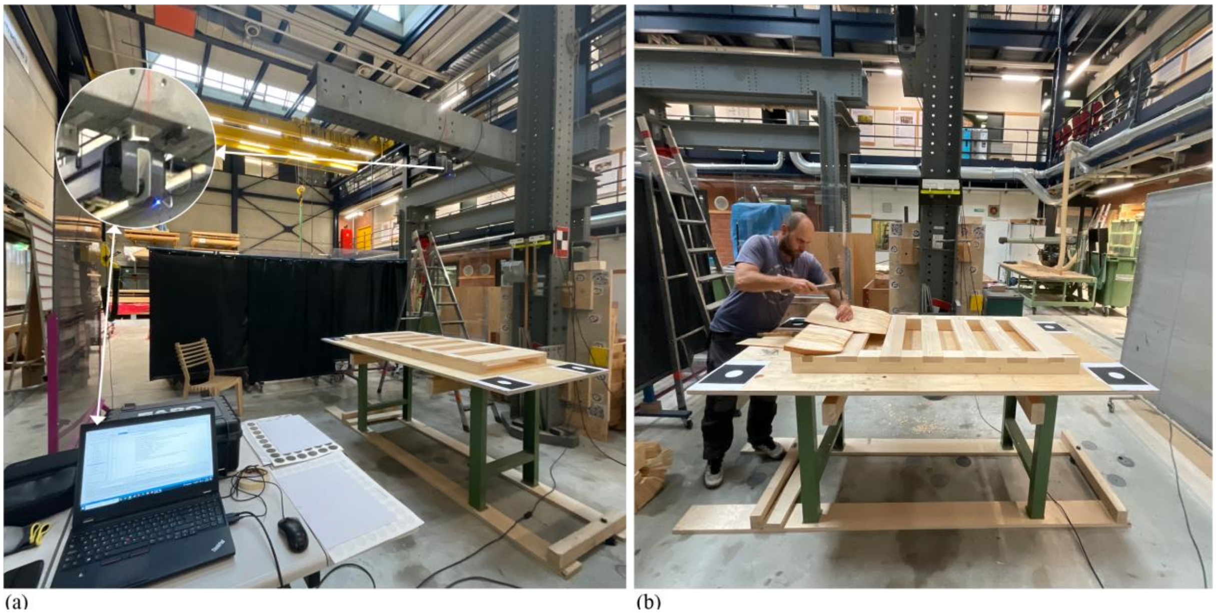

Figure 3. Experiment set-up for the real-time 3D scanning of shingles assembly: (a) A 3D scanner that is connected online via a computer and mounted statically on top of the workspace to provide the 3D scans and transfer the captured point clouds in real-time, (b) A craftsperson assembles the shingles one by one as the process is recorded.

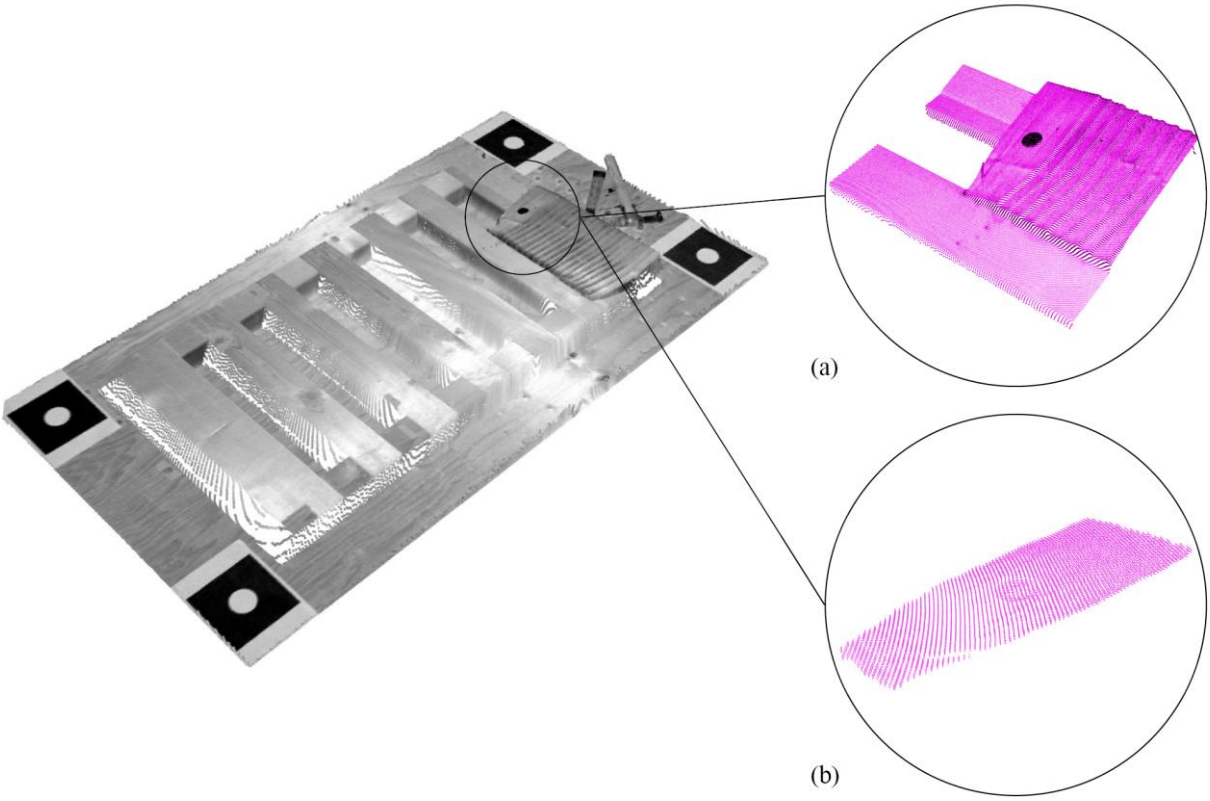

Figure 4. Scanning each shingle after it is placed by the craftsperson: (a) Filtering out the surrounding environment, (b) Clustering the last assembled shingle.

4.2 Experiments and results

Two prototypes are designed and built with two skilled craftspeople, on two types of wooden shingles including tavillons and bardeaux, in order to both validate the proposed methodology and document the details of the two types of shingles. Both prototypes are of a width of 80 cm and a length of 140 cm. A craftsperson builds the prototype in accordance with traditional techniques, and the shingles are scanned one by one. The obtained scans are then post-processed with the above-mentioned methodology, the accurate digital twins of two prototypes were made [30] and the details of the prototypes are documented and will be explained below.

4.2.1 Tavillon

For the first experiment, a prototype was built with tavillons and the following assembly rules were extracted. The first row of tavillons is laid at the lowest point of the substructure, and elements are placed one by one from left to right. The first batten has an inclined surface with a gentle slope, which provides the proper inclination angle for the envelope, thus ensuring the rain drips off the roof. The first row of tavillons consists of elements with a length of 25cm and a width of 10 cm. Each tavillons is placed over the previous one laterally with a side overlap corresponding to 1/5 of their width, such that only 2cm of the tavillon width is exposed. Each tavillon always covers 3/5 of the second last one. The second layer is made up of longer tavillons with a length of 45 cm, and a width of 12cm. The horizontal offset is 2.5-3.0 cm (1/4 of the tavillons width). Additionally, the second row should begin 2.5 cm further back from the first row. From the third row on, each layer is composed of tavillons of the same size as the second row. However, the horizontal overlaps correspond to 1/3 of the tavillons width, meaning that only 4cm of each tavillon is exposed and each tavillon covers 1/3 of the second last one. Furthermore, each row is placed over the previous one, with a vertical overlap corresponding to 1/4 of the tavillon length.

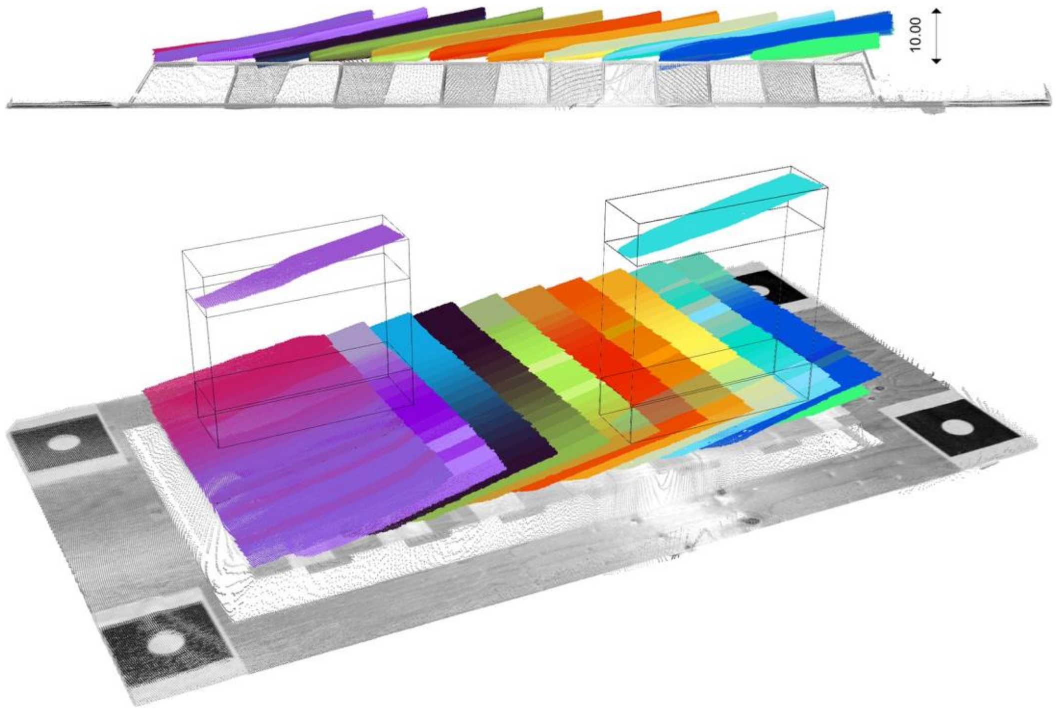

Figure 5. Digital twin of tavillons envelopes

Finally, for the last row, tavillons are placed with the same horizontal and vertical overlaps, but in the opposite direction, such that the thicker side of the material would be placed at the end. In the end, we always have 12 layers of wood (10 cm thickness) at each point of the prototype, which is essential to ensure the water-tightness of the envelopes (Figure 5). Each tavillon is fastened to the substructure with galvanized nails with a minimum length of 5 cm. the nails must be intersected with battens underneath in order to fix the tavillons properly. Additionally, nails can only be applied in the regions that are covered with the next layer, which indicates that we cannot have any nails in the first quarter of the tavillons length (below the exposure line), otherwise, the nails are exposed to rain and would rot, which results in wood decay. Moreover, the position of nails is different for each layer, as the position of the tavillons changes in each layer in relation to the position of the battens underneath.

4.2.2 Bardeaux

For the second experiment, a same-size prototype was built with Bordeaux. Each bardeau was scanned and post-processed using the same methodology as the one used for tavillons. However, the assembly rules are quite different. Just like tavillons, the first row of Bardeaux is built with shorter elements, with a length of 25cm. The elements are placed next to each other with a minimum spacing of 3mm, but unlike tavillons, with no horizontal overlapping (Figure 6). The second row consists of elements with a length of 35cm which are aligned with the bottom of the first row. The elements are selected based on their width, such that they stagger by a minimum of 30 mm, so no seam alignment occurs. The third and fourth rows begin 2.5 cm further back from the two previous rows, with a length of 45cm, and the same staggered pattern. From the fifth row to the third last row, the elements with the same length as the previous row, with a 12cm vertical offset and with the same staggered order are used. For the two last rows, elements with a length of 30-35 cm are used and are placed over each other with no vertical offset, and with a 12cm vertical offset in relation to the previous row. In the end, we have 8-10 cm thickness at each point of the envelope, which is necessary for water tightness concerns. Nails are also positioned with the same rules as for the tavillons.

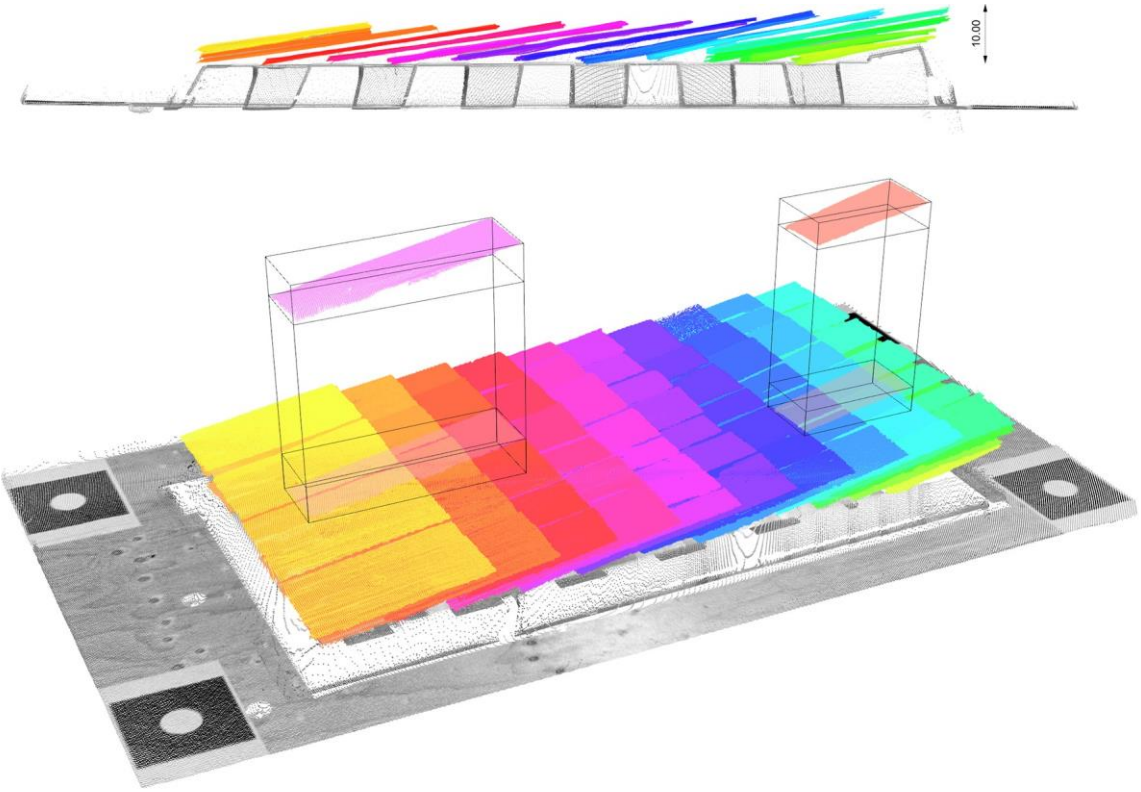

Figure 6. Digital twin of bardeaux envelopes

5. Conclusion

This research demonstrates the first digital three-dimensional reconstruction of vernacular wooden shingle envelopes, along with the details of installation patterns, assembly sequences, and material properties for two types of wooden shingles, known as tavillons and bardeaux, in conformity with craft knowledge. We present a real-time mapping algorithm combined with a vision system that enables the detection of in-progress shingles while a craftsperson assembles them, based on point cloud processing techniques. Unlike most common digital twins of historical buildings, which only provide the exterior surface of the existing buildings' envelopes, in this research, the step-by-step approach for the 3D scanning of the assembly process of shingles produces a fully 3D model of all individual objects, even the elements in the lower layers of the envelope which are covered with topmost layers. The described mapping tools and algorithms could be used for the design automation of wooden shingle envelopes by present-day industries to re-introduce this local raw material in contemporary constructions, which not only would help revive this traditional building system and cultural properties but would also help achieve more sustainable buildings and reduce the carbon footprint of the building and construction sector.

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