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Study case segmented experimental shell

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Published in:
Journal of Applied Geodesy

DOI (link to publication from Publisher):
10.1515/jag-2020-0035

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Kerekes, G., Petrš, J., Schwieger, V., & Dahy, H. (2022). Geometric quality control for bio-based building elements: Study case segmented experimental shell. *Journal of Applied Geodesy*, *16*(2), 151-163. https://doi.org/10.1515/jag-2020-0035

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Geometric quality control for bio-based building elements: Study case segmented experimental shell

https://doi.org/10.1515/jag-2020-0035
Received July 31, 2021; accepted November 20, 2021

Abstract: This contribution presents the prerequisites in the construction process of a bio-based experimental pavilion. A first challenge, is to define tolerances and implicitly measurement tolerances for these materials. After defining them, the focus is set on what can be achieved if geometric quality control is only conducted during the assembly process. Despite using high-end total stations and terrestrial laser scanners in this process, the final pavilion showed discrepancies to its model. In some cases, these were larger than the given tolerances, showing on one side what tasks can be achieved with these instruments and on the other, drawbacks that remain a challenge in bio-based segmented experimental buildings. Finally, an improved workflow is suggested.

Keywords: Bio-based materials, sustainable buildings, quality control, precise surveying, TLS, research pavilion

1 Introduction

Architecture usually includes elements with different manufacturing accuracies. The main structure like columns, foundations, beams, etc. have higher tolerances than detailed elements like windows frames, integrated electronic devices, pipelines etc. A general rule is to fabricate as precise as needed and not as precise as possible; principle that applies for the aforementioned structural elements. The imperfections between elements with different accuracy and tolerance are mostly balanced by filling materials like rubbers polyurethane foams, cement, etc., or by use of subtractive processes like cutting, sanding, etc. The second digital turn in architecture [1] strengthened interest in buildings composed of digitally prefabricated building components with high accuracy (cf. [2]).

The accuracy highly depends on used materials and fabrication methods. Each fabrication method leads to different uncertainties, and it is highly improbable that all the processes will be within the one defined tolerance. Generally, the more precise fabrication is more expensive including waste production and energy consumption. To find a feasible balance some elements have to be fabricated with lower accuracy. Segmented experimental buildings from bio-based materials are discussed as an excellent case study where several iterative processes took place before the segmented structure was erected. Additionally, the individual fabrication steps and their control methods during the process are presented.

Bio-based construction materials have gained popularity as alternative materials for lightweight sustainable building constructions. Often, the bio-based materials are custom made with the help of manual labor. This introduces fabrication imperfections that lead to misalignment during the building processes. Additionally, it is not predictable how the whole structure behaves, since a complex tolerance analysis is only possible if the functional dependencies of all sub-systems (parts) is known (cf. [3]). A method of overcoming later problems in the assembly phase is to verify if the individual parts meet a given tolerance [4]. For this reason, geometric quality control is important in all construction stages (cf. [5, 6, 7]). Deformations caused by weather and own weight during the life cycle of the structure are not discussed, because the focus is set on successfully erecting and assembling the structure. The live span of the structure was about six months. Engineering geodesy offers several methods that cover a wide spectrum of requirements encountered in construction processes [8].

However, two problems are raised concomitantly. One is that there is no standard for bio-based materials and another is the self-defined tolerance within which a part

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would be acceptable for further processing. Since the first one is a matter of subjective decision based on the constructors' (designers') expectation, the second one will be further addressed. Section two presents the workflow necessary for constructing an experimental bio-based pavilion [9, 10, 11, 12, 13]. Further on, section three lays the theoretical frame for the geometric quality control with a total station (TS) and terrestrial laser scanner (TLS), while section four shows the study case of the BioMat pavilion 2018 from an engineering geodesy point of view. Finally, section five ends this paper with conclusions including suggested working process.

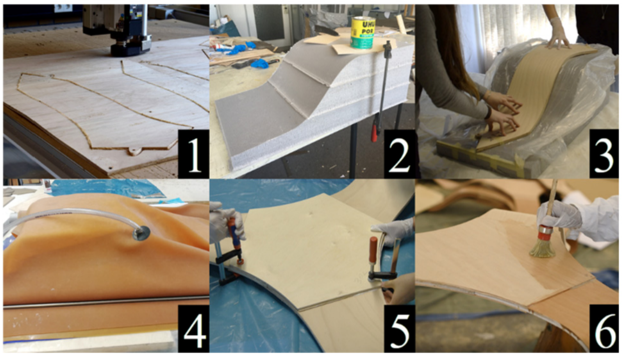

Figure 1: Fabrication steps of Biocomposite sandwich panels (Source: © BioMat at ITKE/University of Stuttgart).

2 Construction process

BioMat Pavilion 2018 is an experimental segmented shell made of bio-composite sandwich elements built in Stuttgart city in Germany. Digital and manual fabrication was combined in several iterative steps, which resulted in ~ 3.6 m height segmented structure covering an area of ~ 55 m^2. The entire process from the initial design to the final erection was a part of two subsequent design studio courses (Flexible Forms). The courses presented a scope combining teaching and research in experimental architecture to investigate methods towards future sustainable architecture using alternative bio-based building materials and digital fabrication methods. In this sense, around 40 architecture students together with researchers from BioMat group (Bio-based Materials and Materials' Cycles in Architecture, located at ITKE: Institute for Building Structures and Structural Design in Stuttgart), as well as diverse international cooperating specialists were involved in the design, fabrication, and assembly procedures following a design philosophy named "Materials as a design tool" [13].

2.1 Fabrication of biocomposite sandwich panels

This process included preparation, lamination, and assembly of 120 sandwich panels from lignocellulosic fibreboards. Each panel consisted of three segments [9].

The following steps were applied during the fabrication process. They are numbered 1–13 for comprehension, as later presented in table 1.

1. The fibreboards were cut by Computerized Numerical Controlled (CNC) process into 360 slightly different segments and post-processed by sanding (fig. 1.1).
2. Four types of universal mould were fabricated by CNC milling of extruded polystyrene (Styrodur®). Wooden dowels were integrated to define exact positions of the segments on the mould. Protective layer from polyethylene foil was placed on the upper surface of the mould (fig. 1.2).
3. The segments were glued in between two sheets of single fibre direction veneer and placed on moulds. Additional layers of polyethylene foil and felt were spread over the mould to protect vacuum bag (fig. 1.3).
4. The segments were formed by vacuum assisted lamination process for ca. 60 minutes (fig. 1.4).
5. Each sandwich panel consisted of three segments. Formed segments were connected to the panels through two layers of veneer sheets, which were glued on the central area of panel from both sides (fig. 1.5).
6. Individual sandwich panels were post-processed by sanding and coating by protective resin layer (fig. 1.6).

Steps 2–6 were produced manually without geometric quality control, therefore influencing the fabrication precision of the segments. The repetitive vacuum process has caused a slight change in the mould, which affected the overall geometric quality. All those aspects had to be considered in the tolerances' definition and further improvement of fabrication strategies.

2.2 Assembly of timber beams and foundation

Due to structural and assembly reasons, three supportive timber beams were integrated in the structure. The beams were fabricated and partially financed by the company Burgbacher Holztechnologie GmbH. In parallel three foundation boxes were fabricated manually. The interconnec-

Figure 2: Fabrication and positioning of timber beams (Source: © BioMat at ITKE/University of Stuttgart).

tions between the beams and the foundation boxes was provided through the steel connectors. The accurate positioning of the beams and steel connectors was crucial for the correct assembly of the 120 interconnected sandwich panels [9, 12]. The process of fabrication and positioning of timber beams and foundations included these steps:

7. Foundation boxes were fabricated manually on site from timber (fig. 2.7).
8. Three foundation boxes were placed on site according to the measured positions (sec. 4.1). Boxes were filled by concrete tiles and gravel to provide sufficient stability. Steel connectors were screwed on the foundation boxes by assistance of TS (fig. 2.8).
9. Three beams were erected with control by TS measurements (cf. sec. 4.4) and fixed through metal plates (fig. 2.9).

Both TLS and TS methods are further described in section 4.3.

2.3 Interconnection of sandwich panels and fixation to the beams

The final interconnection and fixation of the panels reflected the accuracy of the previously illustrated iterative fabrication steps. Four types of interconnections within the panels and beams were determined from the parametric 3D model. The parametric model was used only in a design phase. It included a numbering system to enable better orientation within 120 panels. The panels were connected through bolts and nuts predominately on-site [9, 12].

The process included these steps:

10. Panels were interconnected into four triangular blocks on the ground. Each block contained around 30 panels. The interconnection was done by bolts and nuts through wooden plates with CNC pre-drilled holes (fig. 3.10).
11. Temporary props were positioned according to the TS measurements. Props also determined a position of the central panels (fig. 3.11).

Figure 3: Assembly process and interconnection of sandwich panels (Source: © BioMat at ITKE/University of Stuttgart).

12. Triangular blocks were gradually lifted on the beams and props and fixed to the position (fig. 3.12).
13. Triangular blocks were interconnected in the central part of the pavilion (fig. 3.13).

The assembly process addressed the importance of geometrical quality control during fabrication processes. Each iterative step lead to geometrical imperfections, which gradually cumulated at the end. During on-site assembly the importance of detailed process planning became obvious. Difficulties were recognized when installing panels in space. The correct approach was accordingly set, which was to assemble the segments into triangular blocks on the ground. This offered accessibility to workers and accordingly enabled connections with higher precision. Experience has shown that off-site processes in controlled environments lead to better control of final products. The on-site changing conditions can negatively influence the quality of the segments and the control possibilities. Additionally, a large number of components in the assembly process requires frequent control measurements, which in some cases reaches from very time consuming up to impossible.

3 Quality control

Since there is no standard that precisely defines tolerances for bio-composites, the tolerances were defined by general recognized code of practice (experience) by authors in combination with standards for wood (DIN EN 336 [14] and DIN EN 14080 [15]) and steel (DIN EN ISO 13920 [16], DIN EN 1090-2 [17]). There is a huge variety of bio-based materials which can be applied in architecture [12, 13], therefore it is impossible to have a universal definition for tolerances for all kinds. Further on, focus is on laminated sandwich panels, but the chosen quality control methods are applicable for other types of bio-composites (e. g. composites from long fibers).

There are many measurement methods of controlling the geometric quality of individual pieces or the complete assembly, but the question is which one is the most appropriate from an application point of view.

Discussing geometric tolerance, the acceptance threshold must be firstly defined. In all measurements types this is not equivalent to the instrument measurement precision directly. Usually the quality indicator used in engineering geodesy is the standard deviation, therefore relationships between the standard deviation of a certain measurement method or instrument and the total tolerance must be firstly defined. The total tolerance T is defined as the sum of two kinds of tolerances, T_A tolerance of construction and T_M tolerance of measurement. The term T_A tolerance of construction is also given by the sum of two kinds of tolerances, one for fabrication and one for assembly, but the issue is not further addressed here. Only the minimum number formulas are given for understanding, the rest can be consulted e. g. in [18]:

$$T^2 = T_M^2 + T_A^2 \tag{1}$$

The tolerance of measurement is usually specified with the help of a proportion factor p (value usually 0.3) which defines the ratio of the measurement tolerance T_M to the total tolerance T. Thereafter relation between measurement tolerance, tolerance of construction and standard deviation of the measurement σ are given by:

$$T_A = (1 - p) \cdot T \tag{2}$$

$$T_M = T \cdot \sqrt{1 - (1 - p)^2} \tag{3}$$

$$\sigma \leq \frac{T_M}{2k} \tag{4}$$

where k represents the quantile of the corresponding distribution function. Usually a normal distribution with a 95 % confidence level is assumed, returning a value for k of approximately 2. More about tolerances can be consulted in the normative DIN 18202 [19] and 18710-1 [20].

Knowing these requirements, the geodesist is responsible to correctly choose adequate instruments and methods for reaching the tolerances. An example to outline this aspect is the quality assurance of individual parts during the process. Each part can be controlled with mechanical, optical or electro-optical methods and inspected for processing failures. This is typical for industrial measurements, where metrology instruments are implied in all stages of the production process. Examples are theodolite-measurement systems, Laser Tackers (LT) or video camera-based systems [21].

Choosing the optimal method is among others, a matter of the required measurement tolerance, necessary measurement time and data processing (see tab. on next page). First the tolerances are defined and then explained. With regard to each processes, the decision needs to be made between area-wise and point-wise measurement methods. Explanations are give after the detailed description of the individual tolerances.

In the following paragraphs, table 1 is further described. All decisions for the suggested control instruments are commented including defining of tolerances. Suggestions on fabrication methods and critical reflections are given towards future optimized fabrication of bio-based materials including higher precision and geometry control.

1. Process of CNC cutting of boards is mainly influenced by precision of CNC machine and used material. The CNC milling machine provides higher accuracy (≈ 0.1 mm) than the given tolerance for CNC cutting (1 mm). The tolerance is conducted empirically from material behavior (crumbling) during fabrication. Hand-sanding was necessary for cleaning of cut edges. This process can lead to small inaccuracies, therefore 1 mm tolerance is defined by the authors. The used control instrument in this case (ruler) proved to be rudimentary, because differences in sub-millimeter domain are barely distinguishable. In the future, the LT is suggested only to control sample boards because it offers flexibility in choosing to verify only some characteristic points or a limited surface (in combination with a probe).
2. Quality of fabricated mould has significant influence to accuracy of panels. The given tolerance 1 mm for CNC milling is based on material properties of used Styrodur® board. More stable material (aluminum or SikaBlock®) of mould is suggested to provide higher geometric accuracy. The chosen material affects also the mould assembly including gluing with 1 mm tolerance. The mould assembly can be skipped by using of CNC milling machine with higher operating space or robotic arm. In this case, the LT would be used to verify the material behavior as stated before, either for characteristic points or surfaces.
3. The repetitive using of mould during vacuum assisted process led to its deformation, which is mainly influenced by applied material (Styrodur®). 3 mm tolerance is defined by authors as a maximum acceptable deflection of Styrodur mould. The material of the

Table 1: Biomat pavilion construction processes (cf. sec. 2) with tolerances and control instruments and methods.

Process	$T/T_M/\sigma$ (mm)	Used control instrument	Suggested control instrument
1. **CNC cutting of boards**			
CNC cutting	1/0.7/0.2	Ruler	Laser Tracker
Hand sanding	1/0.7/0.2	Ruler	Micrometer
2. **Fabrication of mould**			
CNC milling of Styrodur® mould parts	1/0.7/0.2	Ruler	Laser Tracker
Mould assembly	1/0.7/0.2	Ruler	Measurement arm
3. **Mould behaviour**			
Mould deformation during a time	3/2.1/0.5	Ruler	Handheld scanner
Position on mould	2/1.4/0.4	Ruler	Measurement arm
4. **Vacuum assisted process**			
Shifting of veneer layers during lamination	2/1.4/0.4	Ruler	Handheld scanner
Deformation of segment during lamination	1/0.7/0.2	Ruler	Handheld scanner
5. **Completion of sandwich panel**			
Gluing segments into sandwich panel	2/1.4/0.4	Ruler	Vernier
6. **Post-processing of sandwich panel**			
Sanding	2/1.4/0.4	Ruler	Micrometer/
Coating	3/2.1/0.5	Ruler	Handheld scanner
7. **Foundation boxes fabrication**			
Fabrication geometric quality of foundation boxes	5/3.6/0.9	Ruler	Ruler
Fabrication geometric quality of steel connectors	2/1.4/0.4	Ruler	Measurement arm/Vernier
8. **Foundation boxes position**			
Position of foundation boxes on site	4/2.9/0.7	Total station	Total station
Position of steel connectors on foundation boxes	2/1.4/0.4	Total station/	Total station/
9. **Fabrication and erection of beams**			
Fabrication geometric quality of beams	10/7.1/1.8	Ruler	Terrestrial Laser Scanner
Erection and assembly of beams	20/14.3/3.6	Total station	Total station
10. **Interconnection of panels into blocks**			
Position of screws	2/1.4/0.4	Ruler	Measurement arm
Assembly to four blocks (on ground)	40/28.6/7.3	Ruler	Total station
11. **Temporary support**			
Position of temporary supports (used as template)	4/2.9/0.7	Total station	Total station
12. **Fixation to the beams**			
Position of blocks (panels) on Timber beams	50/35.7/9.1	Ruler	Terrestrial Laser Scanner
13. **Interconnection of blocks in central part**			
Position of the blocks after interconnection in the air	50/35.7/9.1	Total station/Supporting template	Total station/Terrestrial Laser Scanner

mould effects also accuracy of position of segments on the mould for which 2 mm tolerance was conducted as acceptable. If the material suggestion from step two is respected, step three can be skipped. In this case, a handheld scanner (HS) and measurement arm would confirm if the mould is deforming. Only area-wise methods deliver enough information to decide if the mould can be further used or not.

4. The given tolerances for vacuum assisted process is based on observation of panels after their lamination. During the lamination veneer layers can slightly slide off the core (≈ 2 mm) as well as sharp edges of segments can slightly deform (≈ 1 mm). Inaccuracies have an aesthetic rather than geometric/structural effect. Author´s recommendation is to prepare both cores and veneer sheets slightly bigger and cut out excessive material during post-processing. The point cloud captured with a HS can be compared with a reference CAD model and if irregularities occur, they can be corrected during the process. As in many nominal-actual comparisons, firstly, a best-fit adjustment between the model and the point cloud is performed and afterward differences are computed.
5. The given tolerance 2 mm for gluing of segments is based on manual positioning of segments before being glued. This step can be skipped when panel is laminated as one piece. Only the material thickness is verified here, therefore a vernier (classical or digital) is ideal for point-wise checks of the material thickness.

6. The post-processing includes sanding and coating of panels. Sanding can balance deflections coming from previous processes as well as to increase them when it is not controlled. Hence 2 mm tolerance is conducted empirically. The coating and its thickness should be considered already in the design phase. The quality of coating has significant influence on final assembly, because unwanted droplets on panel surface negatively influence precision of connecting interface. For the manual coating used in pavilion the given tolerance is 3 mm (size of droplets). Both processes should be controlled and ideally automatized to reduce the given tolerance. An automated scan process is possible if the hand-held scanner is fixed on a programed robotic arm and each panel is transported on a processing line for verification. A possible draw-back is surface high reflectivity after coating that leads to unwanted effects in the scan. In this case camera-based systems are recommended.
7. For the fabrication of three foundation boxes the tolerance 5 mm is extracted from DIN EN 336 [14] considering manual work. Their precision can be increased by automatized processes (CNC/robotic milling), but for pavilion purposes this was not found feasible. There is not significant suggestion for improvement of foundation boxes fabrication and their geometric control. The steel connectors were prepared by welding of precisely cut steel plates. The given tolerance 2 mm is defined mainly by the limit deviations for angular dimensions of welded steel specified in DIN EN ISO 13920 [16] and DIN EN 1090-2 [17]. Tolerance can be reduced by precise CNC milling instead of welding, but for purpose of the pavilion and material consumption is not recommended. Opposite to other steps, point-wise methods are sufficient in this case. It is important to verify the dimensions and position of fixing holes on the connectors. This can be done directly with a measurement arm and comparison with a nominal model can be done on-the-fly. Alternatively, a vernier can be used to verify single dimensions of the connector.
8. Placing the foundation boxes on site and positioning of steel connectors on them was a typical stake out task. This was achieved with a high-end TS under certain conditions (cf. sec. 4.2). According to DIN 18710-1 [20] and the tolerances defined above, the pursued standard deviation falls into class L5 – very high accuracy. It is disputable if the efforts made to reach this level are justified, since it restricts the instruments to high-end total stations with sub-second accuracy (< 0.3 mgon) and sub-millimeter distance accuracy.
9. Fabrication of three beams was provided by external timber company (Burgbacher Holztechnologie GmbH). The defined tolerance 10 mm is derived mainly from length of the three longest timber beams (≈ 10 m) according to DIN EN 14080 [15]. Using a TLS during the fabrication process can assure a direct control of the beam geometry. After the beam is fabricated, its position is verified with a TS (cf. sec. 4.3). Single point measurements with temporary marked intervals on the beams were made with the multiple purposes. For once, the position of the beams was controlled and compared with the planned one and second, if adjustments of the beam position were needed, the operators knew which part of the beam needed adjustment. The tolerance 20 mm for the final assembly of timber beam structure is based on overall geometric configuration, position of steel connectors, and timber beams deviations. These tolerances have to be also considered in design of interconnections for sandwich panels. In the ideal case, all panels would be fabricated after the beams are erected in order to best fit the actual beam geometry and position.
10. The overall pavilion was divided into four triangular blocks. The assembly tolerance 40 mm is a sum of maximal determined deviations of individual panels (12 mm) along longest side of biggest triangular block. Panels were interconnected by screws on the ground. Position of screws was defined through wooden plates with CNC pre-drilled holes. The empirically determined tolerance of 2 mm did not have an influence on assembly tolerance but rather on aesthetics of connections. For the future easier connecting process panels should already include holes for screws to avoid on-site drilling. Their design will have to consider and balance assembly tolerance.
11. This step is exactly as described in step 8. The main difference is that supports are only temporary, therefore after the structure is erected, they are removed.
12. The tolerance 50 mm for fixation on beams was determined empirically from assembly tolerance (step 10) and tolerance for assembly of beams (step 9). In the ideal case, the block edges would have been marked on the corresponding beam edge, but at this stage only a final control was done with several TLS points for all blocks (cf. sec. 4.4). Most high-end TLS reach the given level of accuracy (9 mm) in a sense of 3D position accuracy within the give ranges (less than 20 m). The advantage of area-wise methods in this case is that all parts (panels) are captured at once. Single TS point measurements as those made for beam control are

also possible, but extremely time-consuming, therefore TLS is the efficient alternative.

13. The given tolerance 50 mm is the same as for fixation (step 12). The same TLS verification may be conducted as in the previous step. The difference at this step is that the pavilion is complete.

All these steps and explanations are meant to highlight the complexity of bio-based assemblies and choices that need to be made for both the designers and controllers. The authors also intended to aid at finding compromises for similar future collaborations.

4 Quality assurance of the assembly process – Study case: BioMat Pavilion 2018

4.1 On-site prerequisites & reference network

The complete fabrication process of the pavilion made out of bio-based materials is exemplary shown in parallel with analyzing the tolerance requirements previously presented in tab. 1. This gives an indication about which measurement method is adequate and if the tolerance requirements were met.

Examples are given based on measurements made with a Leica TS30 0.5" TS and Leica HDS7000 TLS. More details and an in-depth understanding about TS instruments can be consulted in specialty publications like [22] or [23], whilst for technical details and functionality of TLS, the review of [24] is recommended.

A reference 3D geodetic network that can be used for the following purposes: site survey in 3D; stake out of specific positions, control measurements during and after assembly and final area-wise measurement (TLS scan) is required. Such a network was created for the planed site and network points were marked accordingly so that they are suitable for TLS and TS measurements. After measurement, TS observations have been adjusted with a least squares free network adjustment method in the open source software (JAG3D [25]) and a local coordinate system has been defined. The resulting network covers an area of 30 × 30 m.

As a network quality indicator, it is mentioned that the confidence ellipses have semi-axes with dimensions between 0.3 mm and 0.5 mm (probability of error $\alpha = 5\,\%$). These small values make the network appropriate for further measurements that require high accuracy. As regards the TLS network points these were marked by two types of contrast targets. Firstly, printed water-proof Black & White (B&W) targets were permanently fixed on clear surfaces on-site. Secondly, Leica B&W tilt & turn targets with magnetic bases were temporary fixed on metallic surfaces. For the temporary targets, the position had to be reproduced for each scanning session. This issue was solved by marking the position of the magnetic base on the surface. Finally, the coordinates for the contrast targets were verified in each session via TS direct measurements without a reflector. Even if this is not the best way to create a common TLS and TS point, the approach proved to be a convenient. For future networks that have common TS and TLS points, solutions based on interchangeable reflectors and contrast targets with the same geometric center are recommended.

4.2 Stake out foundation and sustaining plates

First steps of the construction process imply placing the weight foundation on their planed position (fig. 2 B + tab. 1 foundation position). Theoretically two edge points per foundation would suffice, but since the assembly process does not guarantee that the three foundation are exactly as planned (cf. tab. 1), all five corners (see fig. 4) were staked out. This gave the possibility to directly verify if the manufactured foundation comply with the designed ones. As it was not allowed, according to the building regulations in the selected building site, to anchor foundation to the ground; the foundation footages were superficially placed

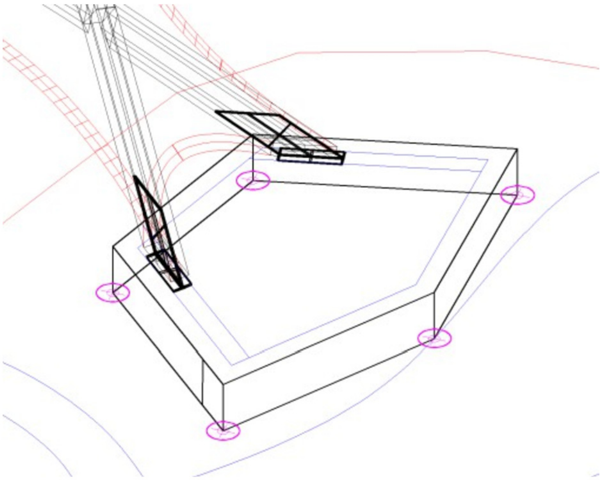

Figure 4: Foundation and stake out points (*purple*).

with imbedded loose heavy weight aggregates to provide the necessary stability. The accurate positioning of those superficial foundations was crucial for the stability of the whole structure. In that sense, edge markings of the foundations' footages also played a huge role in controlling correct positioning. Potential structural deterioration or movements would have been visually detectable if they occurred. For the stake out, the TS was used in combination with a mini-prism. The standard deviation requirements (cf. tab. 1 $\sigma_x = \sigma_y = 0.7$ mm) were achieved under the following conditions: the station point was chosen in such a way that no measurement distances are longer than 10 m and both instrument faces were used for the stake out. For each instrument face the stake out position was temporary marked with one color and the geometrical average point of these two was finally marked. To give an example of the a-prior standard deviations, a point situated at 7.5 m from the instrument leads to a standard deviation of 0.5 mm in the measurement direction and 0.3 mm across. If these values are compared with the requirements stated in tab. 1. step 8, it can be concluded that the method and instrument is appropriate in this case and under the mentioned conditions for future similar tasks. Noteworthy is that only the 2D position was of interest for superficial foundations (see sec. 2.2 step 8) and no height modifications of the construction site are allowed.

Next steps involved the positioning of the metal plates on which the beams were fixed (see sec. 2.2 step 8 & 9). Because these plates had to be fixed on the upper part of the foundations and sustain the timber beams in the same time, on-site control during the assembly was necessary. Before fixing the metal plates, their temporary positions were verified with TS kinematic measurements (reflector tracking) and indications in form of displacement vectors were given in real time. The whole process was made iteratively with continuous changes and inspection of the plates position. The level of achieved accuracy was worse compared to the foundation stake out, but this is directly related to the real time positioning requirement. It is a well-known fact, that standard deviations of TS measurements are higher in tracking mode [26]. After the plates were fixed, the corner points had errors of position above 2 mm, therefore the stated standard deviations in tab. 1 (step 9) were not reached. An alternative seen from the engineering geodesy point of view, is to use a real time network of robotic TSs [27] and track the same reflector (360 ° mini-prism) with multiple TSs from a favorable geometric constellation [28]. It is expected that by this means the position can be improved.

4.3 Control of beams and sustaining structure

One of the most important steps in the assembly process was the beam positioning (cf. fig. 2.9). Correctly positioned beams ensured an as-designed shell form of the covering shell structure. This was verified using the same TS and measuring points on the external upper edge of each beam. Each station point was positioned at about 5 m approximately perpendicular to each beam (cf. sec. 4.3 & fig. 5). The inaccessible points on the beam edges were measured without a reflector. According to tab. 1 the beams assembly required a standard deviation of 1.8 mm for measurements. This is assured only in the case of accessible points that were measured with a reflector. For the inaccessible ones, the distance measurement accuracy taken alone is 2 mm according to the instrument manufacturer [29]; therefore, the tolerance is at its borderline of acceptance. To overcome similar issues in the future, the authors suggest temporary mounting small reflector foils on the inaccessible points. By this means, the distance measurement accuracy is improved, thus improving the control quality.

For each measured point, a difference vector was calculated by projecting its position perpendicular on the beam. To make it clearer, the vector was presented through a horizontal component and a vertical one (fig. 6 above, 6 down). This was seen as a geometric quality indicator for the set-actual position of the beam. The horizontal component showed how much the beam deviated from its

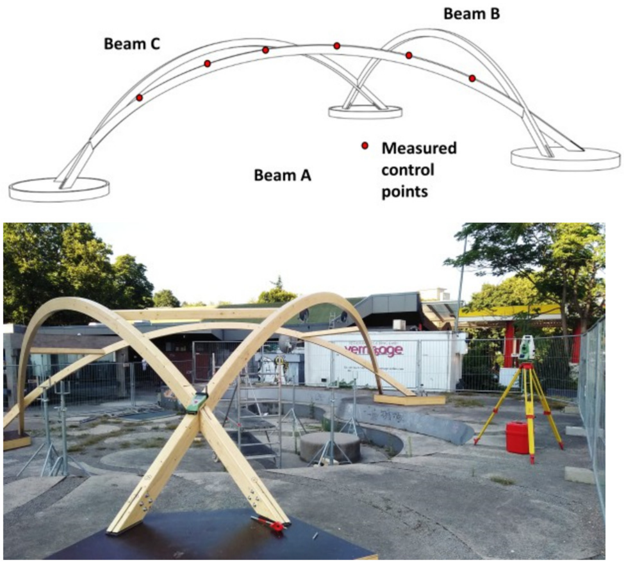

Figure 5: Above: Beams and control points on the outer edge (Source: BioMat/ITKE); down: control measurement configuration.

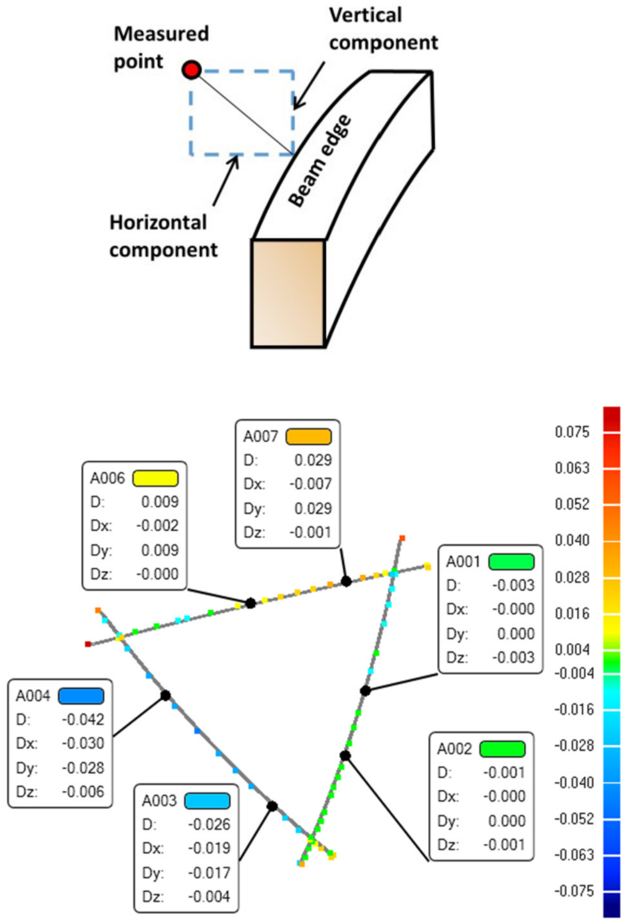

Figure 6: Above: separation of vectors to measured point on the designed (model) beam edge; down: measured control points and difference vectors (mm) for each edge.

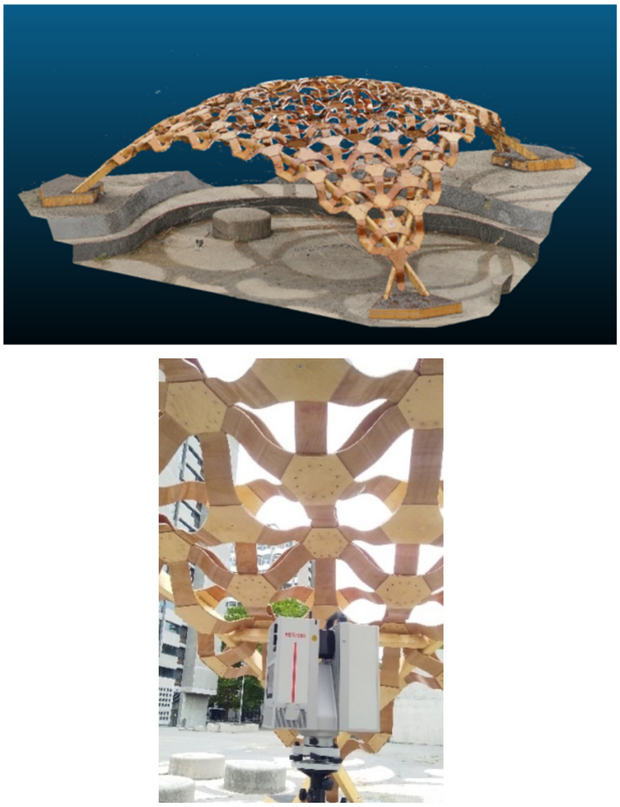

Figure 7: Above: Final point cloud in color; down: example of a scan position under the pavilion.

planned 2D position and the vertical component indicated whether the beam was above (+) or under (-) its intended height. Correcting the position was possible by loosening or tightening the bolts at the beam joints and sustaining plate.

As explained in section 2, the individual panels were assembled off-site and were afterwards joined into four bigger triangle blocks (cf. fig. 3.10). These were temporary sustained by metal props placed in the middle of the pavilion aligned parallel to each of the opposite beam. The props positions were indicated by TS measurements exactly as described in section 4.3. Finally, the triangle blocks were placed and the props were removed.

4.4 Pavilion geometric control

It has been seen that individual pavilion panels (cf. sec. 2) and the position of each panel was relevant for the final structure. Nevertheless, controlling the geometry of each panel of the shell for example by TS measurements (cf. sec. 4.3) after the pavilion was finished, would have been an intensive and time-consuming process. The alternative was to scan the pavilion from many perspectives and then compare the geometry with the given reference geometry (3D parametric model). Figure 7 up shows the result in form of a colored point cloud, whilst fig. 7 down presents one scanner position under the finished BioMat Pavilion 2018.

It is mentioned that the reference frame contained contrast targets with coordinates in the same coordination system as the planned parametric model, therefore a direct analysis was possible and differences were evident on the whole structure. The complete process that allowed this could be summarized as follows: firstly, the construction site is scanned and referenced in a coordinate system, afterwards the model is placed into the same coordinate system (in Rhinoceros), and finally the model-measurement comparison is made without the need of additional model-measurement alignment algorithms. For the indirect georeferencing [30], a total of 143 correspondences were established between all seven station points and the con-

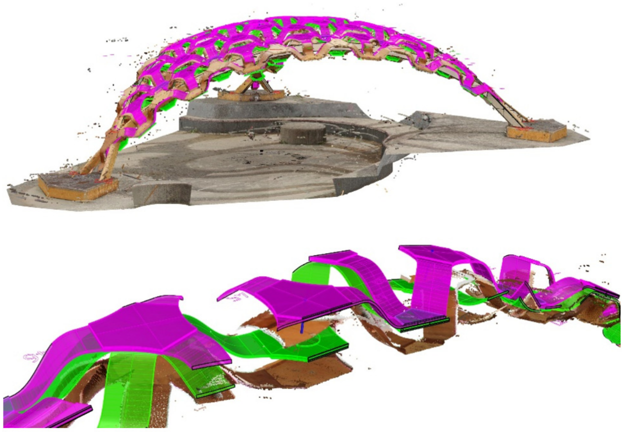

Figure 8: Model to point cloud comparison, above: complete shell, down: 3D Section in central position of pavilion.

Figure 9: BioMat Research Pavilion 2018 (Source: © BioMat at ITKE/University of Stuttgart).

trast targets. This number was not the maximum possible because not all targets were visible from all station points or the target middle point has not been correctly extracted from individual scans (e. g. partially obstructed target). Despite this, the overall RMS registration error, as defined in Leica Cyclone, was 1.7 mm. More about georeferencing can be reviewed in [31].

With the georeferenced model, a visual comparison can be made between the complete set-actual geometry of the pavilion. An example is given for one part of the model, where it can be seen (fig. 8) that at this stage, the blocks positions tolerances became meaningless, since the whole structure was ca. 20 cm lower than the planed one. This was partly due the fabrication quality of individual pieces, beams and on-site conditions during assembly. This can be later optimized by more automatized and control process.

Finally, the BioMat Research Pavilion 2018 (fig. 9) was completed after 10 months of intensive work including design, fabrication, and assembly. Obviously, this represents only a glimpse of several years of research invested in the application of bio-based materials and various concepts for a future-oriented sustainable architecture.

5 Conclusion

Outcomes point out the importance of quality control before, during and after the assembly process. In the case of the research BioMat Pavilion 2018, geometric quality control and assurance was done only on-site during the construction process as well as after erection. For this reason, integrating the quality control methods presented in this paper is absolutely necessary in all stages and not only on-site. Additionally, better applied materials and fabrication methods are believed to deliver better results, but the cost question must always be in foreground, since the perspective purpose is to use these materials for buildings and structures and not only research purposes. This is why the definition of tolerances and achievable quality is primarily important. From an engineering geodesy point of view, two measurement methods (point-wise and area-wise) were used. Classical methods like TS stake out and marking of points can be successfully further applied for other similar structures in different stages. Special tasks, like real time control within the assembly process require different approaches, like the use of a network of TSs. Regarding area-wise methods, TLS scans are useful for quick nominal-actual comparisons after the structure is complete, but the georeferencing is in this case of utmost importance. In pre-processing, the authors assume that many problems can be avoided by verifying components before, for example with hand-held scanners prior to assembly. However, this assumption needs to be verified with a future structure out of bio-based materials. Another research question is the need for integration of engineering geodetic processes into the pre-fabrication process as well as the complete life-cycle monitoring [32].

From the fabrication point of view several steps can be further improved. Involving more optimized processes accompanied by usage of higher standard materials will require higher costs and precise planning. This has to be considered and critically compared with required output quality. Despite the quality of fabrication, which was highly influenced by working conditions and limited resources, the

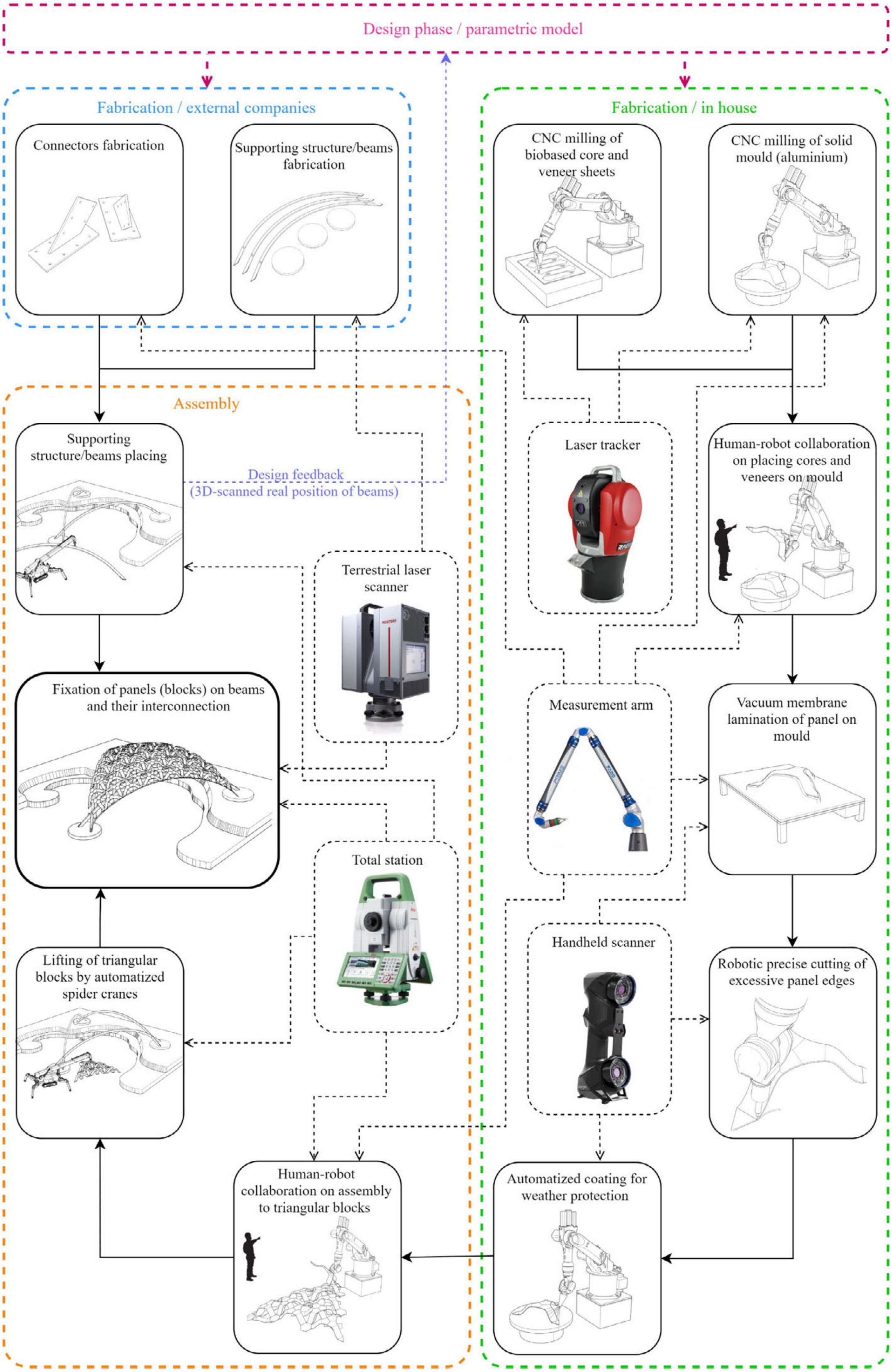

Figure 10: Suggested working process of BioMat pavilion 2018 with recommended control instruments (Images source: sketches – authors, handheld scanner © AMETEK GmbH Creaform Deutschland, other instruments – IIGS University of Stuttgart).

authors see a critical point in the workflow when individual pieces were fabricated and designed before the erection of supporting beams. This fact should be addressed in similar segmented building elements (segmented shells, facades, etc.) through higher required tolerances or by precise 3D scanning of supporting structure. In case of Biomat pavilion 2018 the recommended workflow was not used because fabrication of 120 panels took most of the time, which needed to be done off-site before the on-site work started.

The diagram on the previous page presents an optimal working process of pavilions together with recommended control instruments (fig. 10). The workflow is applicable for similar bio-based building elements including segmented shells, biobased facade panels, discrete structures, etc. where highly precise modular (discrete) elements are installed on supporting structures with higher tolerances.

Acknowledgements: This paper used BioMat pavilion 2018 as a case study for discussion about geometric quality of biocomposite building elements. We would like to acknowledge for support within pavilion fabrication as well as geometric quality study.

Fabrication:

Pavilion Fabrication was supported by German Agency for Renewable Resources (FNR) under the Ministry of Food and Agriculture (BMEL) by project “Bioprofile: (co-)extruded profiles from bioplastics reinforced with plant residues.”

This project is also an associated project (AP 08) with Cluster of Excellence Integrative Computational Design and Construction for Architecture (IntCDC) partially supported by the DFG under Germany’s Excellence Strategy—EXC 2120/1—390831618.

We thank all students, employees, technicians and agencies involved in this project. This work was the direct result of cooperation between around 40 architecture students over two semesters participating in the (Flexible Forms) Design Studio in the semesters: WS17/18 and SS18 supervised by Hanaa Dahy, the director of BioMat group at ITKE with her team: Jan Petrs, Piotr Baszynski and Michaela Mey, with the support from the University of Stuttgart and the Baden-Württemberg Foundation. Financial support was from the German Agency for Renewable Resources (FNR) under the Ministry of Food and Agriculture (BMEL), and scientific cooperation took place with Fraunhofer-Institut für Holzforschung (Fraunhofer WKI) and industrial partners Mathias Stange ETS and Profine GmbH in the framework of the Research Project (BioProfile) FKZ 22021516. International collaboration has taken place with the Technical University Eindhoven in the Netherlands (TU/e) – Department of Built Environment Prof. Patrick Teuffel, Dr. Arjan Habraken and M. Sc. Dirk Bos, in addition to local collaboration with various institutes of the University of Stuttgart, including the Institute of Construction and Structural Design (KE) – Prof. Ulrike Kuhlmann and Mr. Janusch Töpler as well as the Institute of Engineering Geodesy (IIGS) Prof. Volker Schwieger and Gabriel Kerekes. Wooden beams were fabricated and supported by Burgbacher Holztechnologie GmbH with assistance of Mr. Steffen Haller, weathering resistant coatings were provided by Hexion Stuttgart GmbH.

Geometric quality study:

The study was a supported by Research Project (06) of the Cluster of Excellence Integrative Computational Design and Construction for Architecture (IntCDC). It is partially supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy EXC 2120/1-390831618.

References

[1] Carpo, M. (2017) *The second digital turn: design beyond intelligence*. MIT Press.

[2] Krieg, O., Schwinn, T., Menges, A., Li, J.-M., Knippers, J., Schmitt, A., Schwieger, V. (2014) *Biomimetic Lightweight Timber Plate Shells: Computational Integration of Robotic Fabrication, Architectural Geometry and Structural Design*. In: Block, P., Knippers, J., Mitra, N., Wang, W. (eds.) Advances in Architectural Geometry 2014. Springer, London.

[3] Mannewitz, F. (2005) Tolerance Analysis of Arbitrary Physical Systems, ATZ 10/2005 Vol. 107.

[4] Schmitt, A., Schwieger, V. (2015) *Quality Control of Robotics made Timber Plates*. FIG Working Week 2015, Sofia, Bulgaria.

[5] Niemeier, W. (2006) *Geodetic Techniques for the Navigation, Guidance and Control of Construction Processes*. Proceedings on 3rd IAG Symposium on Geodesy for Geotechnical and Structural Engineering, Baden, Austria.

[6] Möhlenbrink, W., Schwieger, V. (2006) *Navigation and Quality of Construction Processes*. Proceedings on XXIII International FIG Congress, Munich, Germany.

[7] Schwieger, V., Beetz, A., Wengert, M., Schweitzer, J. (2010) *Echtzeit-Integration ingenieurgeodätischer Messsysteme in Bauregelkreise*. Proceedings of 16th International Ingenieurvermessungskurs, Munich, Germany.

[8] Rinke, N., von Gösseln, I., Kochkine, V., Schweitzer, J., Berkhahn, V., Berner, F., Kutterer, H., Neumann, I., Schwieger, V. (2017) *Simulating quality assurance and efficiency analysis between construction management and engineering geodesy*, Automation in Construction 76:24.

[9] Dahy, H., Petrš, J., Bos, D. H., Baszynski, P., Habraken, A., Teuffel, P. (2019) *BioMat Pavilion 2018: Development, Fabrication and Erection of a Double Curved Segmented Shell from Biocomposite Elements*. Proceeding of IASS Annual

Symposium 2019 – Structural Membranes 2019 Form and Force, Barcelona, Spain.

[10] Dahy, H., Petrš, J., Baszynski, P. (2019) *Biocomposites from Annually Renewable Resources Displaying Vision of Future Sustainable Architecture: Design and Fabrication of Two 1:1 Demonstrators*. FABRICATE 2020, UCL, UK.

[11] Dahy, H. (2019) *Natural fibre-reinforced polymer composites (NFRP) fabricated from lignocellulosic fibres for future sustainable architectural applications, case studies: segmented-shell construction, acoustic panels, and furniture*. Sensors 19(3):738.

[12] Dahy, H., Petrš, J., Baszynski, P. (2019) *Experimental biocomposite pavilion: segmented shell construction—design, material development and erection*. ACADIA Conference 2019, Texas, USA.

[13] Dahy, H. (2019) *Materials as a Design Tool Design Philosophy Applied in Three Innovative Research Pavilions Out of Sustainable Building Materials with Controlled End-Of-Life Scenarios*. Buildings 9(3):64.

[14] DIN EN 336:2013-12, *Structural timber – Sizes, permitted deviations*.

[15] DIN EN 14080:2013-1, *Timber structures – Glued laminated timber and glued solid timber – Requirements*.

[16] DIN EN ISO 13920:1996-11, *Welding – General tolerances for welded constructions – Dimensions for lengths and angles, Shape and position*.

[17] DIN EN 1090-2:2018-09, *Execution of steel structures and aluminium structures – Part 2: Technical requirements for steel structures*.

[18] Schweitzer, J., Schwieger, V. (2011) *Modeling of quality for engineering geodesy processes in civil engineering*. Journal of applied geodesy 5:13.

[19] DIN 18202:2019-07, *Tolerances in building construction*, Buildings.

[20] DIN 18710-1:2010-09, *Engineering Survey – Part 1: General requirements*.

[21] Schuth, M., Buerakov, W. (2017) *3D-Formerfassung – Einleitung*. Handbuch Optische Messtechnik, Carl Hanser Verlag, Munich, Germany.

[22] Schwieger V., Kerekes G., Lerke O. (2020) *Image-Based Target Detection and Tracking Using Image-Assisted Robotic Total Stations*. In: Sergiyenko, O., Flores-Fuentes, W., Mercorelli, P. (eds.) Machine Vision and Navigation. Springer, Cham.

[23] Wagner, A. (2017) New Geodetic Monitoring Approaches using Image Assisted Total Stations, PhD Thesis, TU München.

[24] Kuhlmann, H., Holst, C. (2018) *Flächenhafte Abtastung mit Laserscanning – Messtechnik, flächenhafte Modellierung und aktuelle Entwicklungen im Bereich des terrestrischen Lasserscanning*. In: Schwarz, W. (ed.) Ingenieurgeodäsie – Handbuch der Geodäsie. Springer-Verlag, Berlin, Germany.

[25] Steinbeis Transfer Centre Applied Geodesy (2020) *Java Applied Geodesy 3D Software*, URL: https://software.applied-geodesy.org/en/, last accessed on 03.06.2020.

[26] Ehrhart, M., Lienhart, W. (2017) *Object tracking with robotic total stations: Current technologies and improvements based on image data*. Journal of Applied Geodesy 11(3):131. https://doi.org/10.1515/jag-2016-0043.

[27] Kerekes, G., Schwieger, V. (2018) *Kinematic Positioning in a Real Time Robotic Total Station Network System*. Proceedings of 6th International Conference on Machine Control & Guidance, Berlin.

[28] Lerke, O., Schwieger, V. (2021) Analysis of a kinematic real-time robotic total station network for robot control. Journal of Applied Geodesy 15(3):169–188. https://doi.org/10.1515/jag-2021-0016.

[29] Leica Geosystem AG (2009) *Leica TS30 Whitepaper*, retrieved from http://w3.leica-geosystems.com/downloads123/zz/tps/general/white-tech-paper/whitepaper_ts30_de.pdf, last accessed on 28.07.2020.

[30] Reshetyuk, Y. (2009) *Self-Calibration and Direct Georeferencing in Terrestrial Laser Scanning*. Ph. D. Thesis, Universitetsservice US AB, Stockholm, Sweden.

[31] Pandžić, J., Pejić, M., Božić, B., Erić, V. (2017) *TLS data georeferencing – error sources and effects*. Proceedings of INGEO 2017, 7th International Conference on Engineering Surveying, Lisbon, Portugal.

[32] Schwieger, V., Menges, A, Zhang, L., Schwinn, T. (2019) *Engineering Geodesy for Integrative Computational Design and Construction*. ZfV 4:223.