DESIGN STRATEGIES FOR REPAIR OF 3D PRINTED BIOCOMPOSITE MATERIALS

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Abstract. This paper presents design and fabrication methods for repair of 3D printed biopolymer composites to extend their lifespan. The methods are applied to panels exposed to weathering conditions. The workflow connects initial design parameters with diagnosis and mesh processing operations to identify deteriorated regions and generate a repair pattern for 3D printing. The pattern is informed by the initial and weathered states of the panel to create a continuous design language. This approach anticipates the repair during design stage since criteria for deteriorated region identification can be embedded during the initial panel design. We demonstrate the methods through two repair strategies using conformal 3D printing.

Keywords. 3D printing, biobased materials, repair, lifespan, material heterogeneity, photogrammetry, fabrication integrated modelling

1. Introduction

Biobased materials are maturing in the AEC industries. It is a promising material class since they are renewable, abundant and act as a carbon sink. A particular category is biopolymer composites, composed of naturally derived and biodegradable polymers, such as lignin or cellulose. They are fundamentally hygroscopic materials which react to changes in the environment and their different strength ratios make them more vulnerable to environmental impact (Thomsen & Tamke, 2022), challenging the architectural stability and durability expectations. To increase their lifespan, maintenance and repair regimes need to be formulated that take into consideration their inherent behaviour. Our interests sit in the larger research territory of 3D printing with biopolymer composites (Nicholas et al., 2023; Dritsas et al., 2020), and the use of 3D printing for repair and maintenance.

1.1. TOWARDS A CIRCULAR DESIGN FRAMEWORK

3D printing with biopolymer composites belongs in a broader effort in the AEC

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industry to transition from a linear to a circular paradigm by keeping products in circulation and reducing waste. The circular model principles are illustrated in Ellen McArthur Foundation butterfly diagram (Ellen MacArthur Foundation, 2019). Here, the technical cycle, referring to non-renewables, consists of multiple cascading steps. The biological cycle emphasizes the regenerative nature of biodegradable materials, which create a closed loop. To support these ideas, circular design strategies are implemented in architecture and construction. An example is Design for Disassembly, an approach that emphasises modularity, material separation and reversable connections to enable maintenance, repair, replacement and re-use (Cheshire, 2021). While this method is highly suited to keep technical materials and building elements in circulation, it cannot simply be transferred to 3d printed biomaterials, which emphasise multi-material grading and continuous fabrication. For these materials, an alternative approach is required. Building on Ramsgaard Thomsen et al (2024) expansion through cascading of the biological cycle of the Butterfly Diagram for biopolymer composites, this research project explores design for repair (DfR) strategies for 3D printed biopolymer composites, where repair comes before recycling in the value chain. This aims to expand on the potential of 3D printing with biocomposites, integrate their anisotropic behaviour and as a result, extend their lifespan.

1.2. DESIGN FOR REPAIR

While care, maintenance and repair are crucial in ensuring the continued functioning of the built environment, they are considerations which are often overlooked during the design phase. In a similar spirit but in the context of electronic devices and objects, the repair movement in Northern America and Western Europe is challenging this oversight. This acknowledges the value existing in broken things and the importance of these actions to decrease waste (Oropallo, 2019). One of the concepts of interest is design for repair. Crosby and Stein (2020) argue that design needs to be linked with the value of repair to acknowledge its relationship with the environment. They emphasize this importance by suggesting two strategies. First one is repair as design, where design is seen as the repair practice itself emerging through communities around the globe. Second is repair for design, a strategy for integrating repair thinking in early design stage. This brings forward the idea that repair is not just a fix, but something that can be part of a continuous design process.

In this thinking, 3D printing is proposed as a tool for repair. For appliances, the 3D printing for repair framework consists of diagnosis, re-design, manufacture, and testing phases (Arriola et al., 2022). It is usually used for replacing missing parts, with the opportunity of taking things further by personalizing or improving its design (Terzioglu et al., 2016). The process extends at larger scales, where 3D printing is used to restore architectural ornaments (Xu et al., 2017) or repair spall damage on roads (Yeon et al., 2018). Similar to the framework developed for appliances, diagnosis is a necessary step. Hence, photogrammetry is used to register the damaged area and aid in reconstructing the missing part.

In this paper, we build on concepts of designing for repair to develop DfR strategies for 3D printed biocomposites. We first present design strategies for biocomposite panels to be placed in an outdoor environment as a weather screen. After their exposure, we inspect them. Secondly, we introduce our registration and diagnosis strategies to identify deteriorated regions in a digital environment. This further informs the repair pattern toolpath generation. Lastly, we showcase our results. This paper presents the first iteration of repair, in a continual construction process.

2. Background: 3D Printing Strategies for Biocomposites

Strategies for toolpath generation are necessary to engage with the material's unruly behaviour. For example, research looks at geometries that allow for airflow (Chiujdea & Nicholas, 2020; Rossi et al., 2022). Previous work at MIT presents modelling strategies where nature-inspired patterns can integrate multiple layers of material, performance and environmental responsiveness (Duro-Royo et al., 2018). Hence, tuning geometry density can vary structural, transparency, rigidity and permanence aspects. Recent research shows that generative patterns can be complemented by context information from 3D scanning to respond to its surroundings (Nicholas et al., 2023, Rudin et al., 2022). Our research expands this research field by integrating information from the multiple states of the panel which have been exposed to environmental factors.

3. Methods

3.1. MATERIAL SYSTEM AND FABRICATION SETUP

Our printing setup consists of a robotic arm UR16e equipped with a custom-made extruder connected to a pump which feeds the material. The printing speed is 70 mm/s and layer height is 2,5 mm. Our material system is composed of water, a collagen-based binder, glycerol to which we add cellulosic fibres. It is a thermoplastic material, which is extruded in a melted state. After deposition it cools down resulting in a rubbery, malleable consistency. After a longer drying period it hardens and becomes brittle.

3.2. DESIGN STRATEGIES FOR OUTDOOR BIOCOMPOSITE PANELS

The biocomposite panels are 35x70 cm. They are composed of three layers which have different material strategies and function. The first one is the base layer which integrate fittings to attach to a substructure, the second is a sacrificial overhang layer which protects the base, and a third connective layer which stitches over the first two. The panel geometry is created using a generative growth algorithm which takes as input curves drawn in Rhino to outline the last two layers. The output is two sets of branches along the long and short axis of the panel which create a grid. The growth angle of the branches and the distance between them can be adjusted according to the nozzle size. The panels connect to a substructure through a wooden joint system and four bespoke round connectors placed along the long edges of the panel to minimize warping. Their geometry is accounted for in the toolpath generation. The overhang sacrificial layer is designed to be the most elevated with a printed height of 35 mm from base, an overhang of 30 degrees and a slope profile which varies based on the input curves. Hence, the layer ends with a drip nose aimed to direct water away (Figure 1).

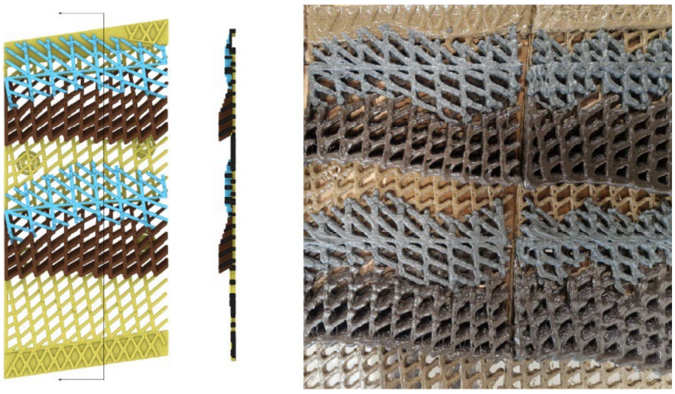

Figure 1. 3D printed biocomposite panel design

The panels are 3D printed on a flat acrylic bed with slots for the fittings. Different cellulosic fibres are assigned to each layer based on colour and fabrication possibilities. Hence, the base layer has wood flour 10% and cotton 1%, the protective layer has 6% bark and 2% cotton, and the connective layer has 6 % cotton. The cotton fibres enable stringing without breaking, which allowed for the connective layer to be printed on the perforated panel created by the first two layers. Furthermore, reinforcing the bark recipe with cotton made possible to print the 30-degree cantilever. As each fibre gives a different colour, we can get a differentiation between yellow base, dark brown sacrificial layer and blue connective layer. This design strategy not only incorporates functional weather protective elements, but the colour and height differentiation are intended to inform the diagnosis process.

3.3. DETERIORATION CONDITIONS

We observed through both human inspection and machine-vision systems the behaviour of the panels exposed to climatic conditions. The exposure period is July to October in Copenhagen, which included precipitation, humidity levels ranging between 33 to 95 percent, and wind gusts of up to 36 m/s. Their hygroscopic behaviour causes warping and shrinkage, leading to receding of the panel edges. Colour change is another a visible impact. For instance, the sacrificial layer darkened, while the cotton lost the blue hue coming from dies. The base layer gained a gradient. The areas underneath the overhang maintained a light-yellow shade whereas in less protected zones it darkened. Another condition is spreading, which leads to loss of definition, especially around the overhang layer. Cracking happens at the thinnest parts of the panels and around the fittings (Figure 2).

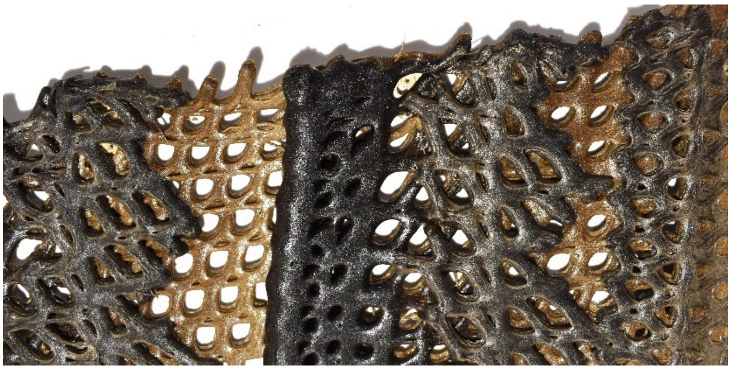

Figure 2. Deteriorated panel

3.4. DIAGNOSIS

The diagnosis process is done through both human and computer processes (Figure 3). The panel is registered through photogrammetry after fabrication and after exposure. To do so, the panel is placed on a bed which has four reference markers used to scale the output geometry to its real size. The geometric and texture conditions caused by weathering are captured from all angles, resulting in a high-resolution mesh.

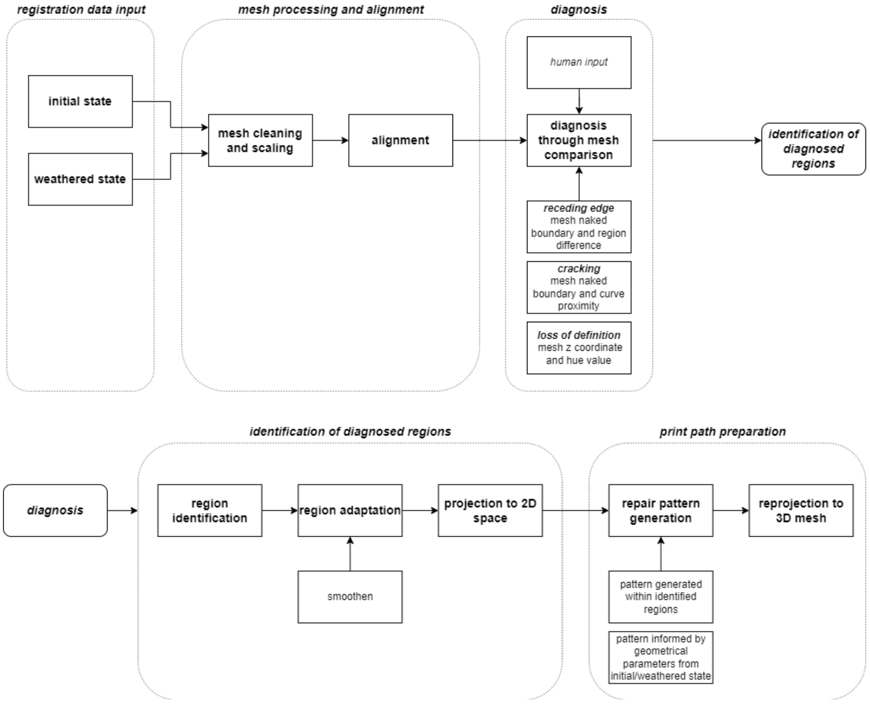

Figure 3. Computational workflow

The post processing consists of automated cleaning, scaling and aligning workflow in Rhino/gh. The edge with the embedded timber fitting is used as a reference for aligning the two meshes, as it has minimal change in shape. Once aligned, the meshes are compared in the diagnosis step. Here, human input is key in assessing what criterion can be used to determine the deteriorated region. The following examples present the process for receding impacts, loss of definition, and cracks, where the criteria are defined by mesh edges, topology and colour information.

Receding edge. Shrinkage is visible at the edges of the panel. The naked boundaries of the initial state mesh and weathered state mesh are used to create a surface defining the region that needs to be infilled. The process is applied per edge (Figure 4, left).

Loss of definition. This affects the functionality of the overhang layer, as its drip nose is no longer sharp. Its geometry is the most elevated part of the panel and darkest in colour, hence the z coordinate and hue value are used to isolate the region (Figure 4, centre).

Cracking. A crack led to the separation of a panel in two pieces. The human places the two pieces next to each other on the photogrammetry bed to be scanned. The diagnosis criterion is the mesh naked boundary, which is extracted for each piece. The edges split by crack are isolated using curve proximity (Figure 4, right).

The identified regions are closed curves which are smoothened and projected to a 2D plane where the repair print pattern is generated.

Figure 4. Left: boundary difference showing receding impact. Centre: Clustering of the overhang layer showing loss of definition, Right: boundary proximity for detection of cracks and missing parts

3.5. REPAIR 3D PRINTING PATTERNS

The repair pattern is informed by the fabrication toolpath of the initial design and the mesh condition of the weathered panel. The print path is generated in the diagnosis output regions in 2D, and then readapted to the 3D mesh of the panel.

3.5.1. Repair Print Pattern for Receding Impacts: the Over-weave

The receding edge is repaired by introducing an over-weaving layer, which fills in the diagnosed region (Figure 5). There are two levels, one located along the edge and bonds to it, and an over-weaving layer which connects the first level to the panel surface. The pattern is a distorted grid where one direction is a tween of curves between the outline of the weathered state and the initial state, and the other direction has a varying angle coming from the initial digital model. Hence, when the grid lines are aligned with the base layer it takes the direction of the base pattern, and when is aligned with the overhang or connective layer it takes the direction of the guide curve of the overhang layer. As a result, there is consistency in the design language, as well as support for other repair actions, such as the redefinition. The density of the pattern depends on the nozzle size. The number of layers is defined by the local heights of each edge. The over-weaving top layer is generated following the same method, however the pattern is extended beyond the panel edge and links to the panel perforations which are still visible. The perforations are identified by segmenting the mesh by z coordinate and extracting closed boundaries in each step. The overlapping ones are removed, and the grid lines branch towards their center point.

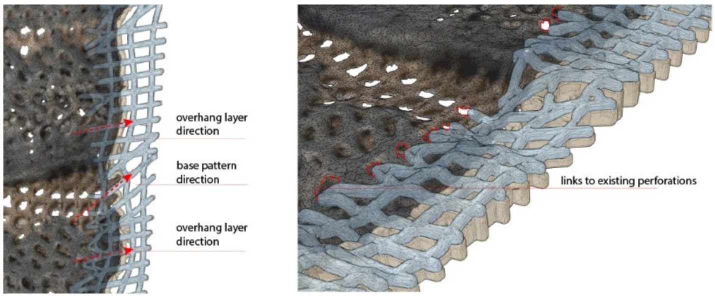

Figure 5. Diagrams illustrating the directionality of the pattern (left), the layer differentiation (right) and the link to existing perforations in the weathered state mesh (right)

3.5.2. Repair Print Pattern for Loss of Definition: the Re-definition

The functionality of the overhang layer is restored by reprinting its drip nose (Figure 6). The diagnosed regions are used to isolate the overhang layer. The toolpath's height, slope and pattern follow the initial design geometry. The number of layers is determined by the height difference between the two states. As the overhang layer has warped edges, the layer number is adjusted accordingly to get a consistent height. The pattern is generated using the same geometric parameters as the initial one. This is a secondary repair operation extending and adapting to the over-weaving layer.

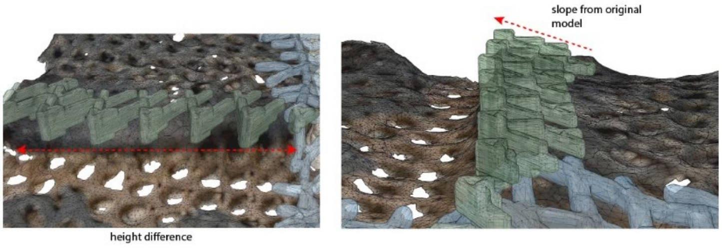

Figure 6. Diagrams illustrating layer variation based on the height difference between the two states (left) and the slope angle of the new geometry (right)

3.5.3. Repair Print Pattern for Cracking: the Patch and Stitch

The panels which cracked in two pieces are joined back together through a 3D printed stitch (Figure 7). A patch is generated where the distance between the two edges identified in the diagnosis step becomes higher than 20 mm. The threshold relates to the nozzle size to achieve a sharp print path, while ensuring support for the stitch print path. The curves are split at the points where the threshold is reached, and the curves become the outline of the patch. The pattern is generated using the same geometry as the initial digital model. The input curve is the midline between the patch outline curves, and the pattern extends to both parts of the panel. The stitching layer uses the same method; however, the input curve is the midline between the edges identified during diagnosis. It crosses the crack and bonds the patch to the panel.

Figure 7. Diagrams illustrating the patch geometry where parts are missing (left), and the stitching geometry which connects the two parts of the cracked panel (right)

3.6. CONFORMAL PRINTING

The toolpath generated in the digital workflow is converted to robot code and sent to our fabrication setup. This experiment showcases the first two repair strategies, the over-weave and the re-definition (Figure 8). The fabrication is done through conformal 3D printing, a printing strategy which responds to non-flat surfaces. Unlike the previous setup used for flat printing, the work object is different. The panel is placed on a printing bed equipped with the same markers as the scanning bed, to align the digital model to the physical setup. To print on the panel and around it, the extruder needs to adapt to the geometry of the panel. Hence, the Z-axis of the plane targets is informed by the mesh normals. We apply a script which adjust the initial plane orientation created using the mesh normals to ensure smooth extrusion and avoid collisions and overflow. This is done through two operations. The first one sets a tilt limit which aligns the planes to a new normal direction. The tilt limit is adjusted via a number slider representing the maximum angle value between the perpendicular normal and the mesh normal. The second operation averages the orientation of a sequence of targets. The number of targets is adjusted via a number slider. The two thresholds are adjusted according to the digital simulation or physical test runs. It can vary depending on the conditions of the panel.

Figure 8. Conformal 3D printing process

4. Results and Discussion

The repair through over-weaving and re-definition are successful examples of 3D printing for repair. The mesh information from the initial and weathered panel states are crucial to create this workflow. As such, boundary difference leads to infilling of an affected area, and mesh topology and colour can be connected to restoring the functionality of the overhang layer. The specification of geometry and material in the initial design stage can incorporate features to aid the diagnosis and repair of biopolymer composites across multiple cycles.

There are limits of the scan data to support accurate identification of regions and features. This is caused both by the quality of the scan as well as the deterioration conditions the panel undergoes. For example, the mesh height and colour information were not sufficient to determine a precise region of the overhang layer in the weathered state. Hence, small areas outside of the region were also selected, which had to be manually removed. In the case of the cracked panel, the two pieces are manually aligned before registration, which can give a different boundary and affect an assembly. As a solution, a laser projector can aid the human to align the two panel parts. Secondly, cracks don't necessarily cross the whole panel. Although they can be identified through naked eye, it is nearly impossible to spot them in the registration output due to the porous nature of the panel geometry. These challenges raise the question, when should repair take place.

The bonding of the new and weathered material during fabrication was successful. However, the limits of the scan also affect the print quality, as the distance between nozzle and panel is not always consistent. The printing can be improved by integrating laser feedback of the real position. The toolpath parameters need some further adjustments, such as decreasing the pattern density to have a precise geometry.

5. Conclusion

In this paper we presented methods of design for repair for 3D printed biopolymer composites. The workflow connects the initial design model, diagnosis and identification of deteriorated regions and generation of an informed repair print pattern. In this approach, the anticipation of repair is already included into the initial design and fabrication stages by specifying geometric parameters and materiality to further inform the diagnosis and repair toolpaths. These parameters, such as overhangs and density variation, can become associated with a repair strategy. Consequently, the design is linked with the value of repair, making repair not only a corrective action but a continual construction and design process. This process takes into consideration and makes use of the inherent behaviour of the material. 3D printing with biopolymer composites is hence expanded in the context of repair, where we can print new panels as well as reprint in dialogue with their changing states within their lifespan.

References

Arriola, J. B., Oudheusden, A. van, Flipsen, B., & Faludi, J. (2022). 3D Printing for Repair Guide. In TU Delft OPEN Textbooks. TU Delft OPEN Textbooks.

Cheshire, D. (2021). The Handbook to Building a Circular Economy (2nd edition).

Chiujdea, R. S. and N., & Nicholas, P. (2020). Design and 3D Printing Methodologies for Cellulose-based Composite Materials. Werner, L and Koering, D (Eds.), Anthropologic: Architecture and Fabrication in the Cognitive Age - Proceedings of the 38th eCAADe Conference - Volume 1, TU Berlin, Berlin, Germany, 16-18 September 2020,Pp. 547-554.

Crosby, A., & Stein, J. A. (2020). Repair. Environmental Humanities, 12(1), 179–185.

Dritsas, S., Vijay, Y., HALIM, S., TEO, R., Sanandiya, N., &Fernandez, J. (2020). Cellulosic Biocomposites for Sustainable Manufacturing (pp. 74-81)

Duro-Royo, J., Zak, J. V., Ling, A., Tai, Y.-J., Hogan, N., Darweesh, B., & Oxman, N. (2018). Designing a Tree: Fabrication Informed Digital Design and Fabrication of Hierarchical Structures.

Ellen MacArthur Foundation. (2019). The butterfly diagram: Visualising the circular economy. https://www.ellenmacarthurfoundation.org/circular-economy-diagram

Nicholas, P., Lharchi, A., Tamke, M., Hasti, V. G., Eppinger, C., Sonne, K., Rossi, G., & Thomsen, M. (2023). A Design Modeling Framework for Multi-Material Biopolymer 3D Printing (pp. 193–206). https://doi.org/10.1515/9783111162683-015

Oropallo, G. (2019). The fixing I: Repair as prefigurative politics (G. Julier, M. Nygaard Folkmann, N. P. Skou, H.-C. Jensen, & A. V. Munch, Eds.; pp. 157–169). Bloomsbury.

Ramsgaard Thomsen, M., Rossi, G., Daugaard, A. E., Rech, A., & Nicholas, P. (2024). Extending the Circular Design Framework for Bio-Based Materials: Reconsidering Cascading and Agency Through the Case of Biopolymer Composites. In M. R. Thomsen, C. Ratti, & M. Tamke (Eds.), Design for Rethinking Resources (pp. 635–646). Springer

Rossi, G., Chiujdea, R., Hochegger, L., Lharchi, A., Nicholas, P., Tamke, M., & Thomsen, R. (2022). Integrated design strategies for multi- scalar biopolymer robotic 3d printing.

Rudin, R., Zboinska, M., Sämfors, S., & Gatenholm, P. (2022). RePrint: Digital workflow for aesthetic retrofitting of deteriorated architectural elements with new biomaterial finishes. Proceedings of the 42nd Annual Conference of the Association of Computer Aided Design in Architecture (ACADIA), 336–345.

Terzioglu, N., Brass, C., & Lockton, D. (2016). 3D Printing for Repair: A Paradigm Shift in Fixing Our Relationships with Things.

Thomsen, M. R., & Tamke, M. (2022). Towards a transformational eco-metabolistic bio-based design framework in architecture. Bioinspiration & Biomimetics, 17(4), 045005.

Xu, J., Ding, L., & Love, P. E. D. (2017). Digital reproduction of historical building ornamental components: From 3D scanning to 3D printing. Automation in Construction, 76, 85–96. https://doi.org/10.1016/j.autcon.2017.01.010

Yeon, J., Kang, J., & Yan, W. (2018). Spall damage repair using 3D printing technology. Automation in Construction, 89, 266–274. https://doi.org/10.1016/j.autcon.2018.02.003