

Article

# 'Materials as a Design Tool' Design Philosophy Applied in Three Innovative Research Pavilions Out of Sustainable Building Materials with Controlled End-Of-Life Scenarios

Hanaa Dahy <sup>1,2</sup> 

<sup>1</sup> BioMat (Bio-based Materials and Material Cycles in Architecture) Research Department at ITKE (Institute of Building Structures and Structural Design) in Faculty 01–Architecture and Urban Planning, University of Stuttgart, Keplerstr. 11, 70174 Stuttgart, Germany; h.dahy@itke.uni-stuttgart.de

<sup>2</sup> FEEDA: Department of Architecture, Faculty of Engineering, Ain Shams University, 11517 Cairo, Egypt

Received: 21 February 2019; Accepted: 11 March 2019; Published: 13 March 2019



**Abstract:** Choosing building materials is usually the stage that follows design in the architectural design process, and is rarely used as a main input and driver for the design of the whole building's geometries or structures. As an approach to have control over the environmental impact of the applied building materials and their after-use scenarios, an approach has been initiated by the author through a series of research studies, architectural built prototypes, and green material developments. This paper illustrates how sustainable building materials can be a main input in the design process, and how digital fabrication technologies can enable variable controlling strategies over the green materials' properties, enabling adjustable innovative building spaces with new architectural typologies, aesthetic values, and controlled martial life cycles. Through this, a new type of design philosophy by means of applying sustainable building materials with closed life cycles is created. In this paper, three case studies of research pavilions are illustrated. The pavilions were prefabricated and constructed from newly developed sustainable building materials. The applied materials varied between structural and non-structural building materials, where each had a controlled end-of-life scenario. The application of the bio-based building materials was set as an initial design phase, and the architects here participated within two disciplines: once as designers, and additionally as green building material developers. In all three case studies, Design for Deconstruction (DfD) strategies were applied in different manners, encouraging architects to further follow such suggested approaches.

**Keywords:** design thinking; sustainable building materials; biomimetic; digital fabrication; closed life-cycle; end-of-life scenarios; green materials; Design for Deconstruction (DfD); bending-active structures; segmented shell

## 1. Introduction

A key feature of architecture is the constant adaptation of external influences such as culture, climate, and ideologies. Architects have always been eager to develop new concepts, analyze existing problems, and transform them into preferred situations. Architecture is influenced by the changing needs of society. In order to adapt to these demands, there is a constant process of rethinking and improving established typologies. Through innovative new developments, the present spirit of the time (*Zeitgeist*) is used and formed to find sustainable solutions for the architectural and structural problems of our time.

However, the constant further development of architecture's form and function is still continuously achieved by the guidance of a rigid linear design thinking process. This classical design tool is based on a fundamental idea, whose emphasis follows the order: defining the problem, brainstorming, problem solving, and finally, testing [1]. It was this specific design tool structure that made it possible to develop most of the current adapted architectural solutions.

Although many ecological problems could largely be improved by architecture, the approach of applying specific ecologically friendly materials as a first phase in the design approach is still not largely applied. Due to the need for rapid reconstruction and the high housing shortage, the post-war architecture missed a sufficient discussion with important factors such as the ecological influence and the re-usability after the building elements' relatively short life cycle, such as for instance building skins that have an approximate lifespan of around 20 years [2]. The still current guiding principle of the construction industry is anchored in the 'take, make, waste' principle [3]. In Europe, this leads to up to 50% non-recyclable construction waste [4].

The construction sector account for more than 35% of global final energy use, nearly 40% of energy-related CO<sub>2</sub> emissions [5], and almost 45% of global resources consumption. As the global population will grow from seven billion to almost nine billion by 2040, the demand for resources will rise exponentially so that by 2030, the world will need at least 50% more food, 45% more energy, and 30% more water at the same time when environmental boundaries will have new limits to supply, especially with climate change [6]. Aggregate materials and concrete are currently the predominant building materials by weight used in Europe, which together with high-emission materials such as steel and aluminum are responsible for the largest share of greenhouse gas (GHG) emissions stemming from the building sector [7]. This paradigm from cradle to grave is no longer feasible, which is why the search for sustainable alternatives is of great importance.

The multidisciplinary cooperation among experts from different scientific worlds, including specifically material engineering, architecture, and structural engineering, as well as possibly biologists, physicists, and others, facilitates huge benefits in setting new circular architectural design philosophies, in which each scientific branch creates an input in the design process. Through this collaboration, another strategy to start the architectural design process may totally differ. In this case, the whole design can start by selecting a specific alternative material, which can be for instance biomass-based, to have the ecologic feedback that is needed, and can be further combined with smart design methods that enable combining the building elements in a way that allows dismantling options for re-use in a later stage.

In previous research work by Lepelaar et al. [8], the usage of green building materials, especially biocomposites, was considered in the design phase of a pedestrian bridge that was built in the campus area of Eindhoven University of Technology (TU/e) in Netherlands. The researchers here worked in a multidisciplinary manner to meet the mechanical requirements as well as the aesthetic ones.

In this paper, the freedom of design was offered when specified green building materials were set as a start input in the design process. Here, linear design thinking was not applied, and a new circular design thinking, which started with 'Materials as a Design Tool', took place. In this case, the choice of materials—especially bio-based materials—were the starting point, followed by defining and customizing the material properties, applying diverse form-finding strategies using parametric design methods, conducting structural analysis and applying digital fabrication technologies to finally prefabricate the building elements.

In this case, defining building materials became no longer a subsequent step that follows the linear design phase; rather it became the circular design's strong foundation. Accordingly, a new design philosophy was established and practiced. The usage of materials' capabilities as a main input in the design process opened the door to the opportunity to develop more sophisticated solutions to address diverse architectural challenges.

This design philosophy 'Materials as a Design Tool' was combined with concepts that could enable dismantling options, which is referred to as 'Design for Deconstruction' (DfD) [2], to be applied

in the form of small and large-scale mock-up structures. The guiding principles were the applied modular structure systems. In this case, the focus was on the simple and logic design of the individual components. In order to reach a proper economic impact, the individual building elements should be always prefabricated in a suitable handy size to ensure quick assembly and disassembly [9,10] that do not require special training. Computational form-finding and different fabrication methods can with help achieving structural and material-saving efficiency, which can ensure a positive building balance, hence helping in the reduction of the total CO<sub>2</sub> footprint. Therefore, materials cannot simply be regarded as constants. Depending on the desired usage, the selected material should be further developed, customized, and adapted. From the beginning of the design phase, prototyping, mechanical tests, and numerical simulation methods are capable of showing the materials' capacities and structural performances. Material fabrication is also an important factor, because the manufacturing processes, such as for example extrusion, drilling, or casting also have an influence on both the material behavior and the geometrical variations.

The author here strives to find effective ecologic solutions in the building industry through starting with materials as a design tool, where the research and development of sustainable biomaterials is set as a starting point in the architectural design process. The intention is to produce building elements and systems that are CO<sub>2</sub>-neutral, recyclable, and/or compostable, and could be partially if not completely produced from biomass resources. This could be only achievable through close cooperation between architects, engineers, material experts, and others. One of the applied materials in the case studies was biocomposite fiberboards manufactured from agricultural by-products such as straw, which is the annual rest-over released after harvesting cereal crops, bound by thermoplastic and thermoset organic binders. The fiberboard structure was dependent on the different binders and applied fabrication techniques, which together settled the main architectural design drivers.

In the following part, three case studies are analyzed, which highlight the philosophy of 'Materials as a Design Tool' combined by the 'Design for Deconstruction' concept through individual applications. Each of the three pavilions illustrates the benefits of modular construction with green building materials, which were used as architectural and structural elements. The research pavilions were materialized by different green building materials, whether purely structural or not.

Flexible biocomposite fiberboards, [11], elastic wood-based middle-density fiberboard (MDF) boards, and recycled 'cartoon' tubes were chosen as the main materials by the author/architect to be applied as a start driver in the design process. In each case, the selected materials were customized to the needed structural capacities. In the design process, the focus was on not only the usage of bio-based materials, but also above all an in-depth examination of possible end-of-life scenarios, including re-using the building elements that would increase the validation of the circular bioeconomy, which is another scope that is needed regionally, especially at the European level [12].

Biocomposites can act as partial replacement to wood, as well as a partial replacement to the classic fiber-reinforced polymer composites (FRP), as this group of materials lie basically between those mentioned materials (wood and FRP). Accordingly, in order to be able to apply these new alternative sustainable materials, it is always needed to mechanically test them after testing the codes of the relevant materials, such as FRP and wood/polymer composites (WPC), so as to apply standardization and verification to settle how reliable the alternative materials are, according to the frame of Eurocodes, to suit the needed applications in reality. This was especially considered in the first case study, which is the largest prototype shown in this paper. In previous work by the author, the improvement of the fire behavior of other developed biocomposites to suit wider applications in architecture was reached [13].

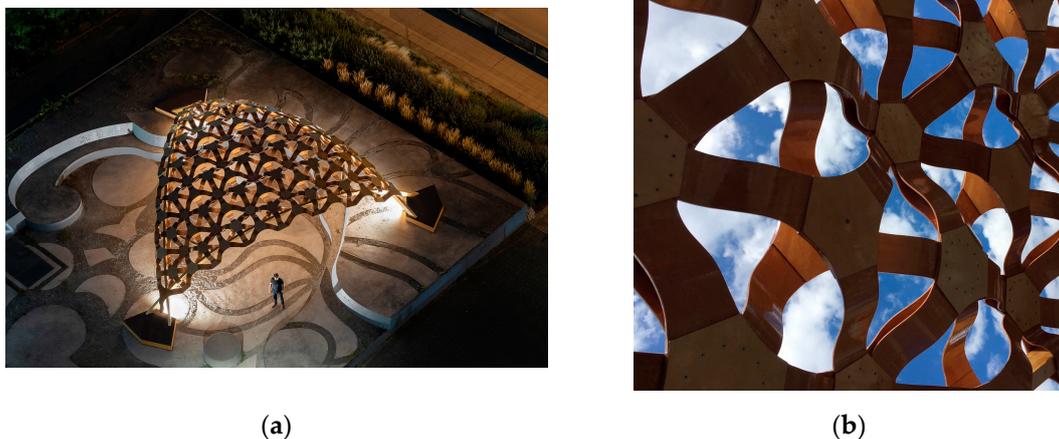
The three analyzed case studies were realized by the Department of Bio-based Materials and Material Cycles in Architecture (BioMat) at the Institute of Building Structures and Structural Design (ITKE) at the Faculty of Architecture and Urban Planning of the University of Stuttgart under the author's supervision.

## 2. Case Studies

### 2.1. BioMat Pavilion SS 2018

The BioMat research pavilion 2017/2018 was the result of close cooperation between architects and external specialists, in which architectural students worked hand in hand with experts from different fields in a multidisciplinary working environment [14]. The 3.6-m high shell structure had a span of 9.5 m, covered an area of 55 m<sup>2</sup>, and was composed of 121 segments fabricated from around 350 digitally fabricated and vacuum-laminated curved segments. It was located at the campus of the University of Stuttgart in the Stuttgart city center in Germany. The modular construction was made of lightweight, single-curved elements that together formed a double-curved shell. The individual parts consisted of a reinforced flexible biocomposite material. The structure was supported by three crossed wooden beams. This design created a delicate aesthetic structure that was possible to dismantle and reconstruct to create new geometrical constellations.

The pavilion was a double-curved segmented shell of single-curved wood and biocomposite elements that were interwoven with each other as a 3D fabric, as shown in Figure 1. The innovative curved biocomposites and laminated plates were developed by the author. The bio-based boards that were applied in the core of the biocomposite laminated panels were exceptionally elastic, which allowed the fabrication of extremely double-curved surfaces of the final shell construction. The elastic biocomposite boards were through computerized numerical control (CNC)-drilled and cut according to the set computational digital design model, and were stiffened through lamination with veneer layers in a vacuum press bag, with no heat or humidity pre-treatment. The resulted engineered biocomposite was adapted to higher stresses and applied as a structural component in the segmented shell construction, serving as the main envelope, and holding its weight and wind loads. The stresses were transferred from the shell to the ground through the cross-linked wooden beams. This 1:1 temporary construction had allowed the testing of the whole developed building system under real conditions for five months between August–December 2018.



**Figure 1.** (a) The erected BioMat pavilion at the campus of the University of Stuttgart; (b) Connections of the modular Design for Deconstruction (DfD) system in combination with structural beams.  
© BioMat/ITKE—University of Stuttgart.

#### 2.1.1. Materials Applied

In order to create a sustainable bio-based system, newly developed bio-composite panels were tested and adjusted to enable structural capabilities that suited their application in the form of segmented shell construction. These biocomposite panels were developed by the author in the form of natural fibers bonded by thermoplastic elastic matrices. The second type of biocomposites applied here were wood-based biocomposite panels that were also vacuum-laminated by veneer layers on

both sides, Figure 2. The special feature of these materials was their flexibility and elasticity. The elastic fiberboards were bendable in any desired single or double-curved shapes, and the final shape was adjusted and customized using three-dimensional (3D) veneer layers, [15,16]. Multiple material alterations were developed in the form of sandwich panels. Different testing for the reinforcements' adjustments took place in order to reach the optimum materials' behavior and the settled target properties and performance. Veneer appliance had caused a large improvement to the developed biocomposites' structural behavior, due to the optimized fiber reinforcement arrangement.

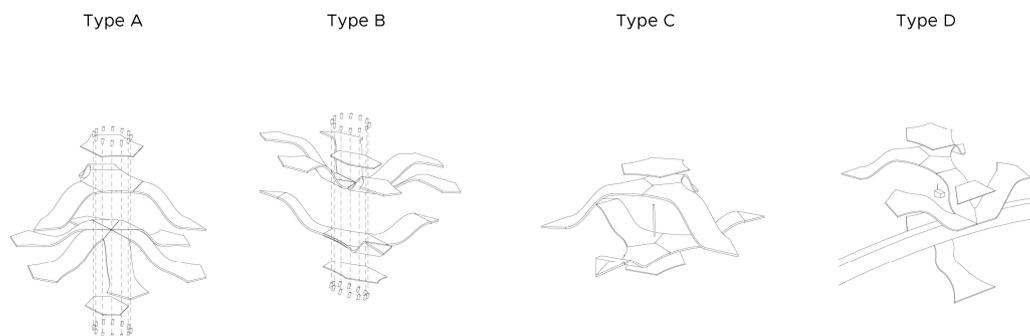


**Figure 2.** Double-sided veneering of flexible biocomposite defines a stable curved shape.  
© BioMat/ITKE—University of Stuttgart.

The internal structure of the biocomposite fiberboards made of natural fibers and elastomers affected the flexibility, elasticity, and structural behavior, depending on the size of the fibers and the mixing ratio with binders [17].

### 2.1.2. Form-Finding, Elements, and Connections

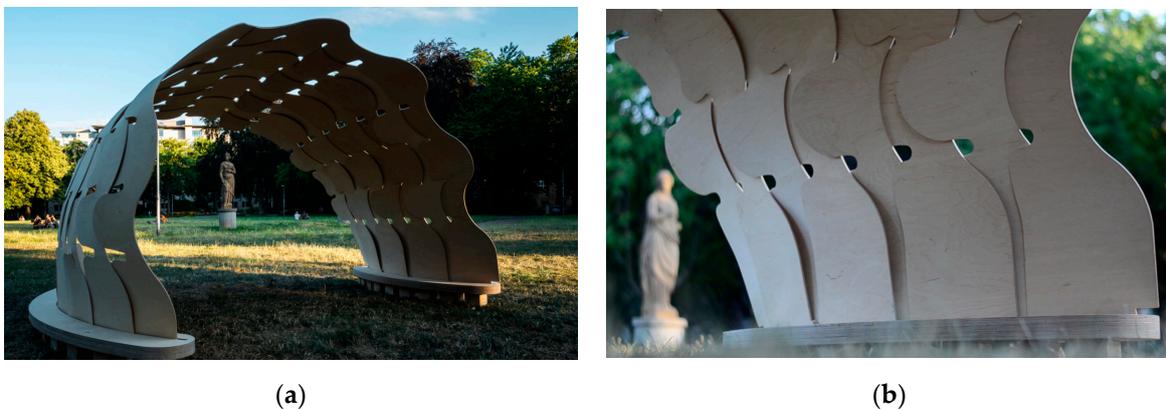
The parametric form-finding process enabled the possibility to find the final applicable architectural solution, in which manufacturing constraints, aesthetics, and structural capabilities were strongly interconnected. The prefabricated components were assembled in four large triangular segments on site that were then lifted to the correct position in space. Four main types of modular connection details were designed and applied throughout the whole shell construction, as shown in Figure 3. Types A, B, and C were the main types of joints between the segmented panels and each other, while type D was the main connection type that was responsible for transferring the loads from the segments to the cross-connected arched wooden beams, and thus onto the foundations. The overall geometry of the shell resembled a 3D fabric in which the curved elements were connected by common knots in all directions in space. This approach allowed the biocomposite sandwich panel elements to be dismantled later at the end of the exhibition to be re-used in other designed constellations.



**Figure 3.** Isometric view of the four main details composed of single curved panels of the modular system. In combination, the single parts create re-usable structural compositions.  
© BioMat/ITKE—University of Stuttgart.

## 2.2. Biomimetic Research Pavilion SS 2018

The Biomimetic Research Pavilion 2018 was the application of a special interlocking system derived from a biological role model function and the translation of those principles into the context of lightweight and material-saving architecture. The research pavilion interlocking system was inspired by Diatoms. Diatoms are a type of algae that usually live in water. Some types are unicellular, and others are able to form colonies in the shape of filament ribbons. The aspect that sparked the idea of taking this biological-inspired concept was that organisms lock vertically, where their spines act as flaps preventing horizontal displacement. Driven by the biological inspiration, the students created a unique design, starting from both the biological role model and the choice of the biomaterial. The system of vertical stacking and interlocking uniform components was translated into a new architecture typology, and by its modular building, the consumption of materials was reduced. In the pavilion, elastic deformation of the longitudinal designed panels was activated. In this sense, active bending was applied through bending and interlocking the panels together and locking the endings in curved footages, reaching a final double-curved shell system, as shown in Figure 4.



**Figure 4.** (a) The erected Biomimetic Pavilion at the campus of the University of Stuttgart; (b) Single pieces with tooth-shaped edges creating a stable interlocking system. © A. Coban and V. Ivanova; BioMat/ITKE—University of Stuttgart

### 2.2.1. Material Properties and Customization

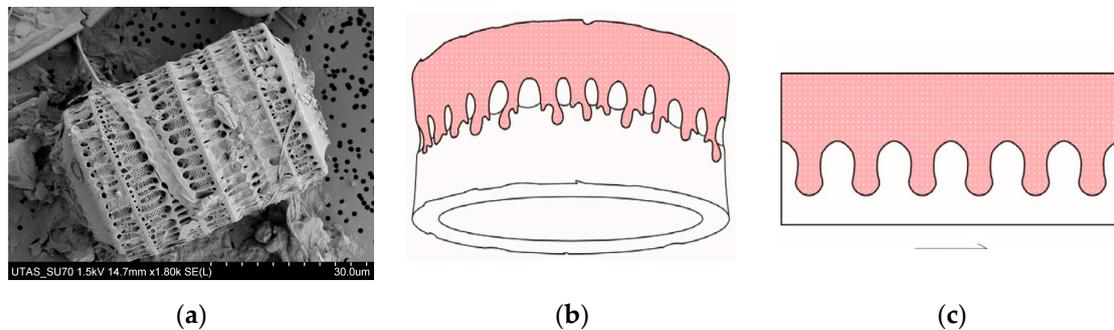
In order to create the double-curved shell structure of the pavilion, 6.5-mm birch wood-based middle-density fiberboard (MDF) plates were chosen to be bent and applied as the main structural material. The MDF was chosen, because it offered sufficient flexibility and elasticity to achieve the needed curvature. Since it is based on wood, the structure enjoyed a high ecological value, especially when the reusability of the elements was enhanced and applied through the special developed ‘dry joint’ bio-inspired interlocking system. The elements were fixed in position inside non-anchored curved foundations with no screws to avoid irreversible shape deformation, allowing at the end through an active-bending appliance to reach up to a double-curved interlocked shell construction.

### 2.2.2. Form-Finding Process

The biomimetic inspiration was based on diatoms, which are the micro-algae creatures that are spread in the oceans and enjoy an interesting interlocking structure, as shown in Figure 5. Looking in depth at the detailing of the naturally existing interlocking structure, the architecture students here have applied several abstraction stages to allow upscaling from the microbiological level to the macroscale architectural realm. The application of this stacking and interlocking system was only possible by means of applying semi-elastic material plates that were bent and interlocked, which shows how customized materials and biomimetic inspiration were both combined and applied. In this project, bending-active structural conception [18] was applied. Bending-active-based construction is

usually reachable when the structural deficiency or buckling of semi-elastic material systems are used to enable new types of structural systems and architectural typologies that are reached depending on the bending behavior and the distributed inner stresses within the structural elements.

In Figure 5, the biological role model is illustrated, and the initial abstraction stages of the interlocking system are shown.



**Figure 5.** (a) *Paralia sulcata* diatom imaged using the University of Tasmania scanning electron microscope (cc) creative commons; (b) Simplification of biological role model of stacking system; (c) Biological stacking system translated into architectonic approach of modular Design for Dismantling. (b,c): © A. Coban and V. Ivanova; BioMat/ITKE—University of Stuttgart.

### 2.2.3. Stacking—A Design for Dismantling

The goal of this pavilion was to achieve a well-developed structural system that could be quickly mounted, dismantled, and reconstructed in different scales and locations. The stacking/interlocking system of the biological role model resulted in the design of various homogeneous building elements with tooth-shaped edges. In this way, an interlocking stable system was achieved by simply pushing the individual parts together, which allowed off-site digital fabrication using computerized numerical control (CNC)-assisted prefabrication, followed by a quick on-site assembly process. The assembly took place in two phases, where at first the pieces were horizontally assembled on the ground in a flat format, as shown in Figure 6a, and then bent and held in shape after connecting the panels' endings to the curved-shaped foundation, as shown in Figure 6b.



**Figure 6.** (a) Simple horizontal stacking by pushing modules into each other; (b) Erecting the pre-mounted pavilion by manual bending, and latter fixation with the curved foundations. © A. Coban and V. Ivanova; BioMat/ITKE—University of Stuttgart.

### 2.3. Eco-Pavilion SS 2011

This research pavilion was built in cooperation with 15 companies and academic institutes, as well as 25 architecture students who participated in the (Do It Yourself) educational course under the author's supervision. The pavilion, which had the dimensions of 4-m length, 1-m width, and 2-m

height, was first exhibited in the foyer of the main building of the Faculty of Architecture and Urban Planning of the University of Stuttgart, after which it was moved and exhibited separately in different locations and exhibitions.

The project combined the use of green building materials, which were used not only as structural elements, but also as exterior and interior cladding, flooring, and decking systems. It illustrated an architectural research approach in which alternative sustainable building solutions with high ecological footprints were applied and exhibited to various audiences, whether academics, students, or users, as shown in Figure 7. This approach highlighted the use of structural solutions, which ensured complete dismantling and deconstruction for later reassembly and the possible change of utilization, using special developed dry structural joints and a modular construction system. The idea of the Japanese architect Shigeru Ban to use recycled cartoon tubes as structural elements in architecture has been transferred to the Eco-Pavilion 2011, in which cartoon tubes were applied as the main structural element of the pavilion in cooperation with a Stuttgart-located architectural office named ‘Architektur Grosse’. The cartoon tubes have been here applied as the structural background to which multiple newly developed green building materials, which were designed and fabricated during the educational course, were fixed. As a result, a framework was established that did not only represent green building materials as recycled cartoon to be applied as structural elements, but also provided the opportunity for other recycle-based and biocomposite-based materials to be applied as cladding systems.



**Figure 7.** (a) Interior cladding applications and hanging partitions of the Eco-Pavilion (left to right): Vacuum thermoformed biocomposite prototypes, hanging partition wall from recycled plastic bottles; (b) Exterior cladding application with free-form facade panels. © BioMat/ITKE—University of Stuttgart. Photos: Miklautsch.

### 2.3.1. Material Choices and Structural Usage

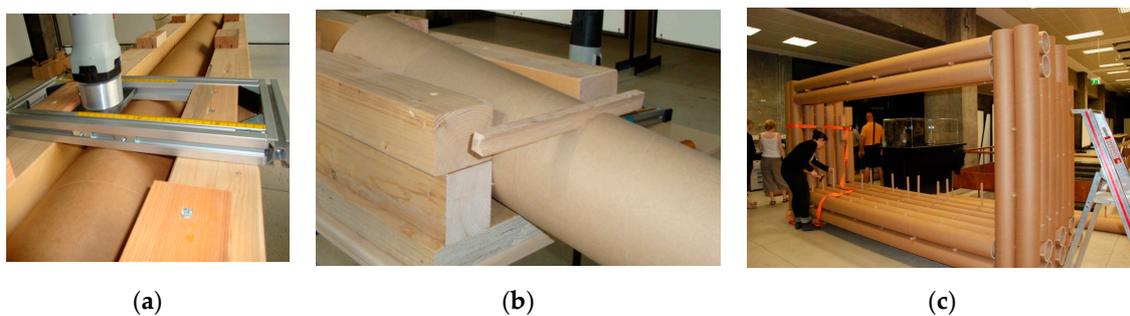
The pavilion was constructed from recycled cartoon pipes that were generated from the recycling of old paper from the solid waste stream, with a lifespan of around five years, to mainly serve in temporary applications and disaster areas. These pipes formed the supporting main structure, which allowed an additional cladding configuration by other materials. Those additional materials that cladded the structural framework were various reinforced biocomposites that were manufactured from agrofibers, including cereal straw short fibers, coconut fibers, and others. The hollow section of the cartoon pipes provided an excellent opportunity to design a sustainable thermal insulation system. This was achieved by filling the hollow pipes with pre-formulated recycled fibrillated cellulose. The fibrils were mixed with paper glue and molded within an open mold to suit the application afterwards of these molded geometries between the pavilion’s cartoon pipes for further thermal insulation.

### 2.3.2. Visual Appearance

The research pavilion's façade consisted of a tile system of individually developed cladding element prototypes measuring  $30 \times 30$  cm, which were named TRASHELL [19]. These biocomposites were designed in free-form style, and through their collective cladding, a desired 3D physical curvature was reached. Non-structural individually developed green building materials, as well re-used plastic bottles that were transformed into threads and combined in the form of panels, provided an ornamental cladding system in the form of an interior hanging partition. For the flooring system, recycled paper and a small fraction of around 20% glass as well as cement were applied as aggregates and for binding, respectively, to form new recycled flooring panels.

### 2.3.3. Design for Dismantling

In order to simplify assembly and disassembly, a connection system was applied that was designed from the architecture office 'Grosse Architektur', which connected the individual cartoon tubes with digitally prefabricated wooden profiles, as shown in Figure 8. The profiles were placed into pre-drilled openings at planned locations of the tubes and then fit at the same size, facilitating connection and enabling deconstruction in a later stage and re-installation with the same or with different designs. This temporary fixed connection was a dry connection method, which did not require adhesives to fit.



**Figure 8.** (a) Fixation of cartoon tubes and drilling holes for further assembling; (b) Pre-drilled holes in desired location for assembling with dry-connection bolts; (c) Interlocking dry-connection wooden bolts ensuring assembling and dismantling of the pavilions' structure. (Photos: H. Dahy)  
© BioMat/ITKE—University of Stuttgart

## 3. Results

In all three case studies carried out between 2011–2018, the philosophy of 'Materials as a Design Tool' was applied, where green building materials were given a priority to be set as the main driver behind the whole design process until the construction phase. The basic idea, which characterized the three pavilions, was to design modular, reusable closed material systems, based on a strong examination of the building material as an initial stage in the design process. The designs of the research pavilions always focused in detail on their own specific architectural challenges and illustrated their implementation through the use and purposeful modification of different green building materials, such as wooden-based fiberboards, recycled cartoon pipes, or biocomposites.

The most recently constructed BioMat Research Pavilion 2018, which was exhibited on the campus of the University of Stuttgart, focused on finding innovative solutions for modifying a flexible, elastic biocomposite material in a way that allowed it to perform structural functions, as well as create a unique aesthetic configuration. The selection and analysis of the materials in the design process determined not only the global geometry of the pavilion, but also the order, size, and shape of the individual elements of the modular building systems.

The Biomimetic Research Pavilion 2018 depended on the analysis of an interesting stacking/interlocking feature of a biological role model. With the help of the abstracted designs, it was possible to develop an assembly/dismantling method to allow full control over the end-of-life

scenarios. The elastic yet self-supporting material properties were also settled in the initial design phase, and for this, wood-based MDF panels were the settled applied materials for this project. Through in-depth analysis, the biological-inspired structures were actively bent and locked in the desired positions to transform the settled integrated concepts into an architectural realm. By this bio-inspired interlocking tooth-like design of individual building elements, a quick dismantling and reassembling was guaranteed. Accordingly, the shell-shaped structure offered the possibility of performing a wide variety of tasks, and could be mounted in different locations.

The third research pavilion, the Eco-Pavilion 2011, was primarily an illustration of the DfD approach combining different green building materials and establishing sustainable building systems. Unlike the other two pavilions, the fundamental idea of the structural framework and the material composition was not re-developed. Here, recycled cartoon pipes were modified by carving slots for the wooden joints, which acted as ‘dry’ structural connections. This recycled and recyclable structure was applied as a background to other biocomposite products, recycled cladding products, and flooring products.

The three research pavilions represent not only the use of green building materials in architectural applications, but also the results of multidisciplinary work. In these projects, architects were not only pure designers, since the close cooperation with external experts naturally expanded the field of the architects’ work. The knowledge gained from material researchers led to functional adaptations of the building materials. The circular design exchange with civil engineers, fabrication technicians, and other external specialists regularly showed the capabilities of introducing the material in the design process, allowing an expression of a new philosophy in design-thinking, based on setting ‘Materials as a Design Tool’. This led to a high level of design creativity and solutions in modular building systems. By constantly adapting to functional demands, the individual components developed their own aesthetics.

In the following, Table 1, an analytical comparison of the three case studies is illustrated.

**Table 1.** Analytical comparison between the three case studies, regarding design, applied materials, DfD, and design freedom. CNC: computerized numerical control.

| Comparison Criteria                           | Case Study 1<br>BioMat Pavilion  | Case Study 2<br>Biomimetic Pavilion  | Case Study 3<br>Eco-Pavilion  |
|---|--|--|---|
| <b>Design Strategy</b>                        | Customizing flexible biocomposite panels into elements with structural capabilities, creating new architectural and aesthetic expressions for future sustainable architecture. | The interlocking system was inspired by a biological role model. Semi-flexible sustainable materials were applied to reach through active-bending new shell design formations. | High ecological footprint by combining green building materials with innovative dry connection system. Modular system applications.                                 |
| <b>Sustainable Building Materials Applied</b> | Elastic wood-based fiberboards; elastic biocomposite fiberboards; 3D Veneer  | Elastic wood-based fiberboards   | Recycled cartoon tubes; wood; cellulose fibers; various biocomposites; recycled plastics and paper  |
| <b>Digital Fabrication Applied</b>            | CNC-assisted prefabrication, vacuum-assisted lamination  | CNC-assisted prefabrication  | Drilling for the dry joints’ slots, robotic drilling for molds’ fabrication of façade cladding system, laser cutting in post-processing of interior cladding system |
| <b>Design for Deconstruction (DfD)</b>        | Yes  | Yes  | Yes   |
| <b>Design Freedom</b>                         | Single-curved elements combined in space in six directions, creating a double-curved segmented shell construction with new innovative spaces and aesthetic expressions.        | Elements are interlocked vertically, bending in one direction, and then locked in a curved non-anchored foundation, leading to a double-curved shell system formation.         | Pre-drilled grid of ‘dry joints’ allow the horizontal or vertical arrangement of tubes.   |

#### 4. Conclusions

The innovative application of newly developed green building materials and their digital fabrication possibilities were the main drivers in the design thinking process, introducing new perspectives of design and establishing new design philosophies. The strong involvement of the choice and characteristics of the materials from the beginning of the design process establishes new ways to develop ideas, which helps solve architectural problems in a much more sustainable way.

Through in-depth knowledge of the properties of these building materials and the ability of further customizing them to reach up to advanced properties and controllable end-of-life scenarios, more sustainable building concepts were developed. The possibility of the individual composition of these green building materials ensured a controlled and directed closed life cycle, which was defined by recyclability, compostability, re-usability, and a holistic improvement of the ecological footprint.

Since the newly developed biocomposite fiberboards were, unlike wood, not bound to a predefined fiber configuration, the same base material enjoyed the ability to function as an insulating, structural, or purely aesthetic building component, according to changes in its internal recipe and by combining it externally with reinforcing elements. That happened especially in the first case study.

In order to ensure further future sustainable solutions within architectural designs and guarantee their implementations, it is important to develop and apply modular building systems that can be assembled and dismantled to allow proper material savings. This will allow the possibility of applying the same building system in different applications. The use of biocomposites and biomaterials with their ability to be adapted and customized to various structural capabilities is a suitable solution for a wide range of new developed architectural applications, which is hereby in many ways proved.

The limitations of this suggested design philosophy's usage of setting 'Materials as a Design Tool' depend on the depth of the architects' interdisciplinary work and the level of their interest in technicalities and other related disciplines to architecture, such as material developments and fabrication techniques. That is why the development of an architectural design process that manifests itself through the choice of materials, structure, aesthetics, and above all, sustainability, was only made possible by a stronger linking of different fields of studies, such as the areas of natural sciences, construction, material scientists, and fabrication experts, and their exchange of experiences. The multidisciplinary exchange allowed the development of more sustainable and intelligent solutions for architectural challenges, since not only a linear exchange of knowledge took place through materials research, but communication between the architects and experts of diverse disciplines was also established.

Adopting 'Materials as a Design Tool' as a design philosophy is hereby initiated from the author, and highlighted through different developments in the form of pavilions and prototypes to spread the word in the architecture community, so as to help initiate this field of design-thinking and philosophy toward more sustainability in the near future of architecture.

**Funding:** The first case study, BioMat pavilion 2018 was funded by Agency for Renewable Resources (German: Fachagentur Nachwachsende Rohstoffe e.V. or FNR) under the Ministry of Food and Agriculture (BMEL) in the framework of the Research Project (BioProfile) funding number FKZ: 22021516. The same case study was also partly funded from the Baden-Württemberg Stiftung and the University of Stuttgart.

**Acknowledgments:** The author would like to thank all of the participants in the development and erection of the BioMat pavilion 2018, including around 40 architecture students over two semesters (WS 17/18 and SS 18) who attended the educational academic course (Flexible Forms Pavilion) and in cooperation with BioMat employees Jan Petrs, Michaela Mey and Piotr Baszynski under the author's supervision. The author would also like to thank the BioProfile project partners including: Fraunhofer-Institut für Holzforschung (Fraunhofer WKI), Mathias Stange ETS, Naftex GmbH and Profine GmbH. BioMat pavilion consultants included: Technical University Eindhoven in the Netherlands (TU/e)-Department of Built Environment-Patrick Teuffel, Arjan Habraken and Derk Bos as well as Ulrike Kuhlmann and Janusch Töpler from the Institute of Construction and Structural Design (KE, Faculty 02: Civil and Environmental Engineering) and Volker Schwieger as well as Gabriel Kerekes from the Institute of Engineering Geodesy (IIGS, Faculty 06: Aerospace Engineering and Geodesy), University of Stuttgart. In addition, the author thanks the students: Arzun Coban and Viktorya Ivanova for designing and fabricating case study 2: The biomimetic pavilion under the author supervision. Also, the author thanks the 25 architectural students who participated in the educational course (Do It Yourself) in the academic semester SS11, which was also at the faculty

of Architecture and Urban Planning of the University of Stuttgart, and participated in designing and fabricating the third case study, the Eco-Pavilion, including the students: Susanne Hügel, Lousia Scherer, and Kerstin Meyer, who designed and fabricated the TRAsH shell product under the author's supervision. The author also thanks all of the partners, companies, and institutes who supported the erection of the third case study, including: Werner Grosse from the Architektur Grosse architecture office in Stuttgart, who designed the structural components of the 'Eco-Pavilion' as well as the companies Kartonagen Müller GmbH and Hoffmann GmbH, for their partial support with the structural cartoon pipes materials and the wooden profiles, respectively.

**Conflicts of Interest:** The author declares no conflict of interest.

## References

1. Plattner, H.; Meinel, C.; Leifer, L.J. *Design Thinking. Understand—Improve—Apply*; Plattner, H., Meinel, C., Leifer, L., Eds.; Springer: Heidelberg, Germany; London, UK, 2011.
2. Crowther, P. *Design for Disassembly—Themes and Principles*; The Royal Australian Institute of Architects, 2005. Available online: <https://eprints.qut.edu.au/2888/1/Crowther-RAIA-2005.PDF> (accessed on 13 March 2019).
3. Scheelhaase, T. *Zukunft: Klimaschutz Kompostierung*; Environmental Protection Encouragement Agency, EPEA Internationale Umweltforschung GmbH: Hamburg, Germany, 2009.
4. Eurostat Statistics. Available online: [https://ec.europa.eu/eurostat/statistics-explained/images/a/a0/Waste\\_generation\\_by\\_economic\\_activities\\_and\\_households%2C\\_2014-1.png](https://ec.europa.eu/eurostat/statistics-explained/images/a/a0/Waste_generation_by_economic_activities_and_households%2C_2014-1.png) (accessed on 19 February 2019).
5. United Nations Environment Programme. Global Status Report 2017. Available online: [https://www.worldgbc.org/sites/default/files/UNEP%20188\\_GABC\\_en%20%28web%29.pdf](https://www.worldgbc.org/sites/default/files/UNEP%20188_GABC_en%20%28web%29.pdf) (accessed on 19 February 2019).
6. United Nations. *Resilient People, Resilient Planet. A Future Worth Choosing, the Report of the United Nations Secretary-General's High Level Panel on Global Sustainability*; United Nations: New York, NY, USA, 2012.
7. Herczeg, M.; McKinnon, D.; Miliotis, L.; Bakas, I.; Klaassens, E.; Svatikova, K.; Widerberg, O. *Resource Efficiency in the Building Sector. Final Report*; Ecorys, DG Environment: Rotterdam, The Netherlands, 2014.
8. Lepelaar, M.; Hoogendoorn, A.; Blok, R.; Teuffel, P. Bio-based composite pedestrian bridge. In Proceedings of the IASS Annual Symposium 2016 "Spatial Structures in the 21st Century", Tokyo, Japan, 26–30 September; pp. 1–10.
9. Kibert, C.J. *Sustainable Construction: Green Building Design and Delivery*, 4th ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2016.
10. Guy, B.; Ciarimboli, N. *DfD. Design for Disassembly in the Built Environment. A Guide to Closed-Loop Design and Building*; Hendrickson, K., Ed.; Hamer Center for Community Design, The Pennsylvania State University: Old Main, PA, USA, 2008.
11. Dahy, H.; Knippers, J. Flexible High-Density Fiberboard and Method for Manufacturing the Same. European Patent EP3166765A1, 13 January 2016. Based on Same Patent, Also Applied as WO2016005026A1; CN106604806A; US20170144327, EP2965882 A1.
12. Ellen Mac Arthur Foundation. Growth within. A Circular Economy Vision for a Competitive Europe; McKinsey Center for Business and Environment, Ellen MacArthur Foundation Publishing: Cowes. Available online: [https://www.ellenmacarthurfoundation.org/assets/downloads/publications/ElleMacArthurFoundation\\_Growth-Within\\_July15.pdf](https://www.ellenmacarthurfoundation.org/assets/downloads/publications/ElleMacArthurFoundation_Growth-Within_July15.pdf) (accessed on 19 February 2019).
13. Dahy, H. FLEXIBLE FORMS: Experimentieren von Biobasierten Materialien für eine Zukünftige Nachhaltige Leichtbau-Architektur. Available online: <https://www.architekturblatt.de/flexible-forms-experimentieren-von-biobasierten-materialien-fuer-eine-zukuenftige-nachhaltige-leichtbau-architektur/> (accessed on 19 February 2019).
14. Dahy, H. *Efficient Fabrication of Sustainable Building Products from Annually Generated Non-Wood Cellulosic Fibres and Bioplastics with Improved Flammability Resistance. Waste Biomass Valorization*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 1–9. [CrossRef]
15. Dahy, H. Natural Fibre-Reinforced Polymer Composites (NFRP) Fabricated from Lignocellulosic Fibres for Future Sustainable Architectural Applications, Case Studies: Segmented-Shell Construction. *Acoust. Panels Furnit. Sens.* **2019**, *19*, 738. [CrossRef] [PubMed]
16. Dahy, H. Biocomposite materials based on annual natural fibres and biopolymers—Design, fabrication and customized applications in architecture. *Constr. Build. Mater.* **2017**, *147*, 212–220. [CrossRef]

17. Dahy, H. *Agro-Fibres Biocomposites' Applications and Design Potentials in Contemporary Architecture: Case Study: Rice Straw Biocomposites*; University of Stuttgart: Stuttgart, Germany, 2015.
18. Lienhard, J. *Bending-Active Structures: Form-Finding Strategies Using Elastic Deformation in Static and Kinetic Systems and the Structural Potentials Therein*; University of Stuttgart: Stuttgart, Germany, 2014.
19. TRAshell Building Element. Available online: <https://www.raumprobe.de/material/universitaet-stuttgart-itke-institut-fuer-tragkonstruktionen-und-konstruktives-entwerfen/trashell/datenblatt/> (accessed on 19 February 2019).



© 2019 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).