Tailored natural components – functional geometry and topology optimization of technical grown plants

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1. Abstract
The prominence of ecologically produced and sustainably operable goods is constantly increasing and society's acceptance is rising. For ecological reasons and for society's demand sustainable materials are thus also of increasing importance in the manufacturing industries. Substituting conventional substances such as metals or plastics is therefore an important issue in the field of product development. Until now, most of the eco-design approaches are limited to the selection of the right material but the industrial processing to manufacture the desired design is done in a conventional way. Consequently a better eco balance can only be expected for material extraction, recycling and disposal while manufacturing is not considered in a way it should be.
The authors of this contribution are scientists from the areas of cell-biology, eco-toxicology, structural-, engineering- and industrial-design. They teamed up to analyse the potential and the behaviour of bio-materials being influenced during their growth period into predefined shapes, which can be produced on an industrial scale and which are used as semi-finished products. The aim is to minimize conventional production steps and thus decrease the amount of resources needed for manufacturing. To find out which products and plants offer promising potential, in the first step possible plants are categorized and analysed in general and on a structural cell level. In addition, requirements and main elementary functions for different sorts of products are defined, and matching parts of both databases are identified. For a systematic approach, engineering methodology e.g. according to Pahl and Beitz is taken as a basis.
It is expected that plants being influenced during their growth will go through a natural topology optimization compared to a plant being reformed and shaped during a manufacturing process after the plant has been cut. A higher grade of mechanical stability can therefore be predicted if the plant is absorbing the same strain while it is growing as it will during usage as a technical product. The aim of this project is to investigate these structural differences in mechanical testing, on a cell level in the laboratory as well as in simulations using Finite Element Analysis (FEA). Bamboo is taken as a first exemplary plant for its high pace of growth.
For a holistic view the potentials of the renewable materials will be evaluated by a comparison to conventional materials considering mechanical properties. Moreover, the assessment of the eco balance of the entire life cycle of a product, the Life Cycle Assessment (LCA), is employed to compare the impact of conventional and renewable materials. The outcome will be a data base with mechanical, ecological and economic information to help the developer to decide which material to choose for which technical product and what ecologic impact is implicated.
2. Keywords: Eco Manufacturing, Grown Components, Technical Product Harvesting, Natural Topology Optimization

3. Introduction
The demand for sustainably produced goods is constantly growing, considering societal as well as political calls. An ongoing process has therefore been to substitute conventional material like plastic or metal by natural, renewable materials. But until now products have mainly been copied using a "new" material without taking advantage of the materials' characteristics and natural topology. The approach in this project is not to concentrate on the topology of the conventional product but to break the product down into its elementary functions. A product with the same function which is made of a different material can therefore look totally different depending on the material's characteristics. The goal is to produce structurally well designed, sustainable products that can be reproducibly manufactured on an industrial scale. The natural topology of a plant is influenced during its growth; thus the plant can grow into a certain shape which can be used as a semi-finished product. In addition to the already better eco balance compared to conventional materials even manufacturing steps can be saved that way.
Additionally it is expected that plants go through a natural topology optimization if the same loadcase is applied during their growth as it will be when the plant is used as a technical product or part. Structural advantages are very likely. The potential of possible structurally gained strength is investigated experimentally and in simulations. The

aim is to formulate design guidelines for different biomaterials with which the potential of these materials can be utilized up to a high capacity. To achieve this, a consortium of scientist from the areas of cell-biology, eco-toxicology, structural-, engineering- and industrial-design has teamed up to work on the task of Technical Product Harvesting (TEPHA). All gathered data about technical requirements and functions and material properties of biomaterial will be summarized and linked in a data base.
In addition to the mainly functional and structural analysis the ecological impact of the whole lifecycle of products is being analysed. The Life Cycle Assessment (LCA) of different products considering their life from cradle to grave is looked at. Also economic data that arises from the manufacturing process until the recycling is considered in the database.
With help of the database the developer, engineer, architect or designer, should be able to choose the right sustainable material considering the function of the product, the ecological impact as well as economic issues. For each case he can decide on his own whether the structural function, the ecologic or economic issues are most important. Approaches and first results of this fresh cooperative research are presented in this contribution.

4. Approach and state of the art

4.1. Approach
The goal is to fully exploit the natural given mechanical und topological properties of sustainable materials. To make sure not to only copy an existing part and substitute the material, the functions of certain representative products are broken down to their elementary functions and requirements. Additionally the goal is to find new applications for natural materials without being prejudiced by already existing products made of those materials.
To achieve this, on the one hand technical functions will be systematically analysed and classified according to the engineering design methodology of e.g. Pahl and Beitz [1], see also 6.1. On the other hand biological data is summarized and clustered considering structural material parameters such as Young’s modulus, Poisson ratio as well as biological data as growth rate and required growing conditions. All data will be stored in a database to eventually find matching partners for fulfilling a certain technical function with a certain natural material. Additionally but independent from the functional parameters the database will include information on ecological data considering the whole LCA of certain products or functions as well as data about economic figures for the use of each material (see 4.3).

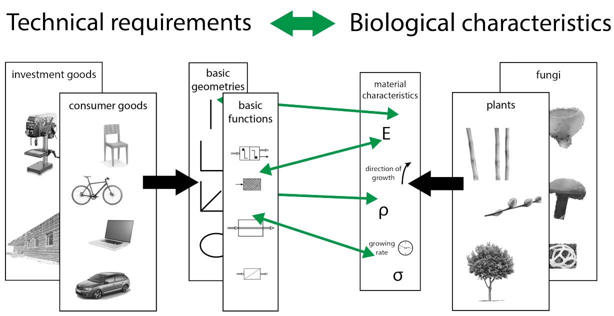

Figure 1: Systematically finding matching technical requirements and biological characteristics

Eventually the database will also contain design guidelines of how to design with the given material. This information is varying for the different bio-material since the natural topology needs to be considered. Information will therefore include growing dimensions, e.g. bamboo is only growing one directional with no branches and is always made of a hollow stem with a certain radius and nodes. When bending a bamboo a certain bending radius cannot be excessed. Whereas a fungus, growing 3-dimensionally, has hardly any restrictions in topology and its structure is usually foam-like with hollow lightweight cells.
To fully exploit the plants properties it is also necessary to analyse to what extend the plant can be manipulated in its growths and what effect the manipulation causes considering structural behaviour. For its rapid growth this scenario is exemplarily tested on bamboo. The experimental and simulative procedures are displayed in section 6.2. The way the plant is presented in this work is to be seen exemplarily. The aim of the project is to investigate numerous species of plants and fungi in a similar way.

4.2. Current use of sustainable material for technical purposes
Current products made of sustainable material that fulfil a technical function and that are produced on an industrial scale do not or hardly take advantage of the natural topology of the plant. To achieve the required shape of a product either external connection pieces are needed or they consist of laminates that require complex manufacturing processes as well as chemical additives. Changing the shape of a whole e.g. bamboo cane takes

place under heat and pressure. Structural damage is expected here. (See Figure 2)

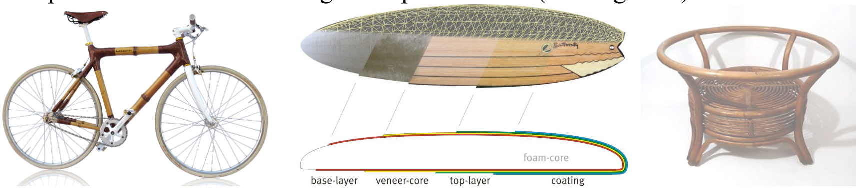

Figure 2: (a) Bicycle made of bamboo [2], (b) Surfboard made of bamboo laminate [3], (c) framework of table

Natural materials grown into certain shapes as design objects have been presented by several artists. The so called "chair farm" by Werner Aisslinger is one of the most famous artefacts. With his installation (Figure 3a) Aisslinger wants to indicate the change in consumer behaviour to a more regional and sustainable demand.
But so far, growing plants and the use of their characteristic shapes have mainly been used as unique artefacts or design objects. The "Pooktre Living Chair" is a well known example. The chair in Figure 3b was planted in 1998 and has been growing since. The new field of botanical construction or "living architecture" is an approach to use the natural topology for technical functions. In German it is referred to as "Baubotanik" and it was estblablished in 2007 by Prof. Dr. Gerd de Bruyn in Stuttgart (Figure 3c,d). But despite its technical function they are unique solutions that cannot be manufactured or reproduced on a large scale.

Figure 3: (a) Chair Farm" by Aisslinger [4], (b) Chair made of a living tree [5]
(c), (d) Natural fixation for a handrail of a bridge [6]

Biomimetic is another current research area. Imitating the topology and its functionality of natural systems is the main aspect. The material employed can be either sustainable or conventional.

Figure 4: (a) Technical/architectural structures inspired by natural growth [7]
(b) Technical Plant Stem as fibrous compound material, inspired by biological templates [8]

Only very little research could be identified where the shape of a living plant is modified and used for technical purposes. The Industrial Design faculty at Monash University, Melborne, Australia concentrated on a rickshaw-vehicle design made of bamboo grown into the shape of the vehicle frame. So far the possibility of manipulating the shape with a certain bending radius and influencing the cross section of the cane could be shown.

Figure 5: Bamboo shape modification over substructures [9]

But until now it is hardly known that the growth itself has been influenced to produce near net shaped structures that are reproducible. Achieving reproducibility on an industrial scale is the major aim to achieve in this project.

4.3 Ecological impact

One of the project goals is to establish a comprehensive life cycle assessment of the near net shape grown components as well as for their conventional equivalents. This allows to evaluate if the bio-based components can be produced more environmental friendly. The LCA of a product covers the whole process from the raw material extraction and acquisition, through energy and material production and manufacturing, to its use and end of life treatment up to the final disposal [10], Figure 6.

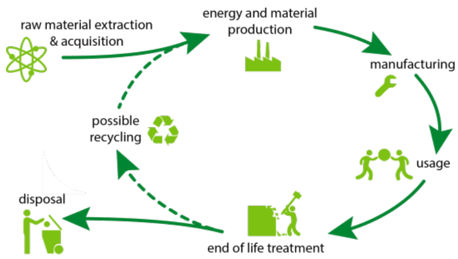

Figure 6: Life Cycle Assessment (LCA)

5. Exemplary plant: Bamboo. Biological background

Bamboo is a tribe (Bambuseae) within the plant family of true grasses (Poacea) which comprises more than 1400 species [11]. Bamboos grow mainly in the tropical and subtropical regions around the globe and are of significant cultural and economic importance in Southeast Asia. Bamboo is used in building, construction, as raw material for plywood or composites and even as bamboo viscose for clothing. A great advantage of bamboo is that some species belong to the fastest-growing plants in the world [12] The culms of Dendrocallamus giganteus can grow within one growth period of a few months to full height (up to 35m) with impressive diameters (up to 30cm). The culms then lignify, harden and incorporate silica to extraordinary strong material [1313131313]. Bamboos produce wooden stems with a higher compressive-strength than tree wood, brick or concrete, a tensile strength that rivals steel and a surface with extraordinary hardness [14]. Lignin is responsible for the high compressive-strength of bamboo wood and cellulose for its unusual tensile- and break-strength [15]. The special organization of the wood in a hollow stem with longitudinal fibers, intersections and the hardest material on the stem-surface produces extraordinary properties. This is why bamboo has received a lot of attention in material sciences.
Hence, to ensure the success of bamboo cultivation under North Rhine-Westphalian conditions, bamboo species were selected based on their frost-resistance. Phyllostachys vivax and Phyllostachys bissettii as two possible bamboo species for the production of near net shape components can tolerate temperatures down to -20°C, resp. -23°C. Moreover Phyllostachys vivax is a very dry resistant species possibly tackling the irrigation issue [16].

6. Procedure

6.1 Methodical approach

According to Pahl and Beitz, in the conceptual state, all technical systems can be described as a combination of several principal solutions. These in turn consist of three elements: “physical effect”, “effect carrier” (material) and the “qualitative embodiment parameters of the working location” [1]. It is obvious that even in this early stage of product development not every physical effect for a given function can be realized with every sort of material or any geometrical shape.

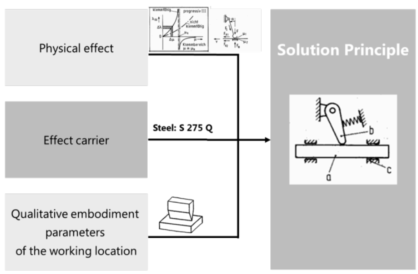

Figure 7. Elements of Principle Solutions [1]

In order to address the technical functions, on the one hand the authors use the Koller approach of elementary functions, which cannot be subdivided to a lower hierarchical level and can directly be implemented with at least one corresponding physical effect [17]. A set of different elementary functions has been defined for the material, energy and signal flow, which can potentially be covered by naturally near netshape grown materials. At the same time, a systematic analysis of a wide range of products from consumer goods to machine tools and plant engineering as well as architecture/civil engineering is carried out to cluster different product characteristics and identify archetypal application patterns for the material substitution. The results are implemented in the product-function database including amongst other parameters information about the three mentioned aspects of the principle solution. The database will thus contain classifications of products which lead to basic functions and required material properties. At the same time the database includes data about growing organisms such as mechanical properties as well as geometric limitations during growth. Besides it will also contain quantitative data on the LCA (Figure 6) and economic data.

Hence with help of the database it will be possible to identify the basic functions of a product. In the second step it will lead the user to the material requirements needed to fulfil these functions. To match the technological requirements and the biological characteristics the requirements are then compared to the material data of the possible natural effect carriers (*Figure 7*). Along with the evaluation of the fulfilment of the technical functions, ecological and economical criteria will be displayed. Ideally the user will then have the choice of different materials and can weigh which aspect next to the functionality is most important for his case. Based on this he may choose a natural substitute for the conventional material.

Since a detailed product not only consists of structural elements or elements which are directly involved in the fulfilment of a technical function, but is also composed of material volumes which do not contribute functionally [17], the embodiment design and styling of these parts need to be considered as well. Particularly it is obvious that not every contour or outline can be realized without additional technological processing.

Currently the availability of adequate material data for the TEPHA approach is very limited, not only in terms of the number of different plant species but also concerning guidelines for controlled and guided growth respectively the alteration of physical material characteristics caused by the manipulation. To overcome this lack of information the consortium has set up different plantings and tests material from the same species conventionally grown as well as according to the outlined method. For the first stage the authors concentrate mainly on structural functions of products.

6.2. Experimental approach

The procedure to analyse the behaviour of plants being manipulated while they are growing consists of different approaches. Bamboo will be manipulated while it is growing. Because the lignification until the bamboo reaches its full hardness takes up to three years, structural testing cannot be done on the manipulated plants. But structural testing can be done on bamboo canes that have grown normally, yet under the same nutritional conditions as the manipulated plants. To estimate the gain of structural strength of naturally grown structures compared to canes with the same topology that have lignified and then modified under pressure and heat, a simulation model is set up.

Experimental growing procedure

For the mentioned advantages in section 5 the first stage of the experiments deals with different species of bamboo. It is systematically tested to what extend bamboo can be influenced in its natural growth.

Different parameters such as bending angles and radii as well as the cross section will be gradually changed to get to know the limits. A variation of tools will lead to the optimal way to create reproducible elements.

Knowing what basic geometric elements are producible, it will be possible to predict what kind of whole products or semi-finished products are contrivable. So far it could be shown that it is possible that the bamboo is manipulable in its shape. The tested plant is growing in a loop of approximately 20 cm (*Figure 8*). In further experiments different species of bamboo and other plants and fungi will be tested.

Figure 8. Bamboo growing in a loop trough a tube

Structural evaluation

Regarding the topology of naturally grown structures such as e.g. trees it is noticeable that these structures develop exactly the topology needed for the loadcase which is applied by wind, rain etc. [18]. The aim of this project is to make use of this characteristic for technical purposes and to quantify the gained advantage compared to plants that have been manipulated after their growth was finished.
Since the lignification of the bamboo needs approximately three years, no structural testing can be done during the two-year-project. But the potential of the manipulated plants can be estimated by setting up a simulative FE-model for straight bamboo. That model can be expanded to simulate the behaviour of bamboo that has been grown into a certain shape since it can be assumed that for both growing scenarios no cells have been injured. Comparing this to the results of structural testing from bamboo that was bent after its lignification, a quantitative prediction can be made about the structural advantage of grown structures.
The goal is to find out to what extend natural growing into a wanted shape has structural advantages to structures that have been bent afterwards.

7. Discussion and Outlook

In the project TEPHA the potential of substituting conventional materials with sustainable bio-material for products that are manufactured on an industrial scale is investigated. By creating a database with which it is possible to evaluate products according to their function and not to their topology it will be possible to find matching natural materials that fulfil the requirements needed for that certain function. The goal is to fully exploit the material properties. To do so design-guidelines for each material will be developed.
For the guideline and to estimate the potential of manipulated grown structures, the structural behaviour is going to be evaluated. In particular for the chosen example bamboo it is analysed how much the grown structure is stronger than the one bent after lignification. This contribution only provides the approach for further research and first supposable qualitative results of this project. It is expected that there will be quantitative results of first exemplary plants soon after the first growing phase when results of simulations and of real grown plants can be verified.
But even if the structural strength will be worse or equal, the eco balance of the grown material is still of better value because of the way the raw material is extracted and because of less manufacturing steps. The authors therefore see great potential ecological wise. Economically the growing time and needed space have to be kept in mind as well as possible tolerances for the produced products. It is obvious that still it remains a natural material that can only be manipulated in a certain range. High production tolerances can therefore not be predicted which limits the selection of possible products.
The presented methodology in which elementary functions are used to choose a certain material could also be introduced for other material groups to ensure best exploitation for certain materials.

6. Acknowledgements

The presented research is funded through means of the German Excellence Initiative.

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