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Growing Near Net Shape Components from Renewable Materials

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Abstract

The integration of natural materials in today’s product development gains more and more importance. Society’s demand for ecologically produced and sustainably operable goods is a key driver for material scientists and engineers to substitute conventional substances such as metals or plastics. In addition, the entire lifecycle sets multiple requirements for the product developers entailing strategies for reuse and recycling. Most of these eco-design approaches are limited to the selection of the right material and the industrial processing, to shape and manufacture to the desired design. The authors of this contribution are scientists from the areas of cell-biology, eco-toxicology, structural-, engineering- and industrial-design, and teamed up to use directed natural growth of bio-materials (e.g. plants). The aim is to minimize conventional production steps and decrease the amount of resources for manufacturing. In the first step the team categorizes and analyzes potential plants in general and on a structural cell level. In addition, requirements for different sorts of products are defined, and matching parts of both databases are identified. The full paper will show first results and research of the potential function-plant relation and will give an overview of characteristic parameters for the holistic evaluation of near net shape grown products. These include exemplarily the amount of fertilizer needed, ecotoxicological implications, plant area needed, growth time, mechanical properties, design restrictions and possible surface quality.

Keywords: Technical Product Harvesting; Grown Components; Eco Manufacturing

1. Introduction

Society’s demand for ecologically produced and sustainably operable goods is a key driver for material scientists and engineers to substitute established substances such as metals or plastics. Substituting conventional for renewable materials with a better Life Cycle Assessment (LCA) has therefore been a successful and ongoing practice especially in the area of consumer goods. The aim of the current research is to analyze the potential and possibilities of substituting conventional material for technical products by taking the advantage of the original shape of the utilized organism and by analyzing the possibilities of letting them grow into the net shape of the final product as far as possible. That way it is not only possible to save resources because of a better ecobalance of the material itself but also to reduce production steps and therefore save resources in manufacturing. At the same time 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.
One of the goals of this research is a database with which it is possible to evaluate the mechanical, ecological and economical potential of substituting a conventional material for a renewable material grown near net shaped. A multidisciplinary team consisting of cell-biologists, ecotoxicologists, structural-, engineering- and industrial designers are currently working on this task. First results of this novel cooperation will be presented in this contribution and the approach will be outlined.

2. General Process and State of the Art

2.1. Approach

What are the requirements so that a conventional product can be substituted by a product made of renewable resources that have preferably grown near net shape, is the main question to be answered. To do so this work comprises a theoretical approach as well as an experimental part to evaluate the theory and the physical limits on exemplary plants and grown products.

To systematically approach the idea and to make sure not to omit any important and potential solution, the engineering methodology according to Pahl and Beitz is taken as a systematic basis [1]. Additionally, ecologic and economic aspects are comprised to holistically evaluate the prospective results. From an engineering (Mechanical Engineering and Civil Engineering) perspective, possible products and use cases are analyzed and then categorized and clustered. This outcome as the basis for the resulting data base comprises information about mechanical, geometrical and material/substantial properties. At the same time data about possible plants and organisms is collected and systematically structured. The data is analyzed to find matching features that allow biological ways to reproduce the required technical properties [Fig. 1].

The main focus here is to find processes with little environmental impact that are able to generate reproducible goods. This can start with near net-shape grown plants up to influencing the cell structure of certain organisms in order to modify their growths, shape and structural behavior.

In the first stage of the experiments it is analyzed to what extent it is possible to influence the growth of a living cell/plant in terms of imposing it into wanted directions and shapes. This is exemplarily tested on one specific plant which shape is systematically modified during its growths. The outcome can be transferred to akin species of plants and to similar geometrical modifications. Different species will be worked with in a later stage.

All gathered and developed data will be summarized in a database.

2.2. Current applications of organisms for technical purposes

The majority of those products have been made of relatively naturally grown plants that are being altered in a manufacturing process to create their required net shape. Either the original solid state with external connecting elements, single fibers or cells in a composite or biomass such as starch for biodegradable plastics have been utilized for different kind of products. [Fig. 2]

Still growing plants and their characteristic shapes have mainly been used as unique artifacts or design objects. Such as the “Pooktre Living Chair” or the new field of botanical construction (German: “Baubotanik”, estbl. 2007 by Prof. Dr. Gerd de Bruyn, Stuttgart) [Fig. 3].

Another current research field is the biomimetics where natural systems are imitated for technical purposes but not the plant itself is being used [Fig. 4].
Only one project could be so far identified where the shape of a living plant was modified. In a university project an Industrial Design faculty concentrated on a rickshaw-vehicle design made of bamboo grown into the shape of the vehicle frame [Fig. 5]. They could show that it was possible to manipulate the shape of the cross section as well as the bending of the cane.

But until now it is hardly known that the growth itself has been influenced to produce near net shaped structures that are reproducible on an industrial scale.

Additionally the authors work focusses on the natural limits when manipulating the growth of a plant. Furthermore the structural behavior is analyzed. In particular the structural difference and strength between those near-net shaped grown plants and plants that are manipulated after they have been cut and those that are connected with external joints is investigated. The approach to do so is based on current engineering design methodology and therefore not focusing on certain products but kept as general as possible.

To analyze the potential of influencing the plant in its growing phase in a possibly short timeframe, a plant with a preferably rapid growth is required. Thus as a first exemplary plant bamboo was chosen here as well. Its main biological, technical and ecological properties as well as current applications are introduced in section 4.

2.3. 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 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. [3], [4], Fig. 6.

3. Design Methodology

The use of natural materials grown in shape as design objects has been introduced by several artists. One of the most known artifacts is the so called “chair farm” by Werner Aisslinger. The aim of his installation (see Fig. 7) is to indicate the change in consumer behavior to a more regional and sustainable demand.

Even though this installation is a single handcrafted object and no mass produced article, it addresses two prevalent trends of the market: An increased responsibility of customers in terms of the use of resources and the necessity of addressing aesthetic needs.

Thus, requirements of products can not only be categorized in several technical or economic fields, but also contain semantic functions. The share of semantic functions ranges from zero (ideal product) to 100% in case no practical function is realized (artwork) [Fig. 8]. Altshuller states that real life products i.e. physically existing items are subject to sensory perception and carry semantic functions [6].
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”, “function carrier” (material) and the “qualitative embodiment parameters of the working location” [Fig. 9], [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.

In order to address the technical functions, on the one hand the authors use the Koller approach of elementary functions, which can not be subdivided to a lower hierarchical level and can directly be implemented with at least one corresponding physical effect. A set of different elementary functions has been defined for the material, energy and signal flow, which can potentially be covered by naturally in near-netshape grown materials. On the other hand, 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 structural properties of different natural effect carriers and geometric limitations both during growth and for function fulfillment are compared with product requirements by technical, semantic, economical and ecological criteria.

Since a detailed product not only consists of structural elements or elements which are directly involved in the fulfillment of a technical function, but is also composed of material volumes which do not contribute functionally [8], 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 (TEchnical Product HARvesting) 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 (see section 4.4).

4. Biological Characteristics

4.1. Biological Background

Plants are photoautotrophic organisms that use the energy of sunlight to convert atmospheric CO₂ into biomass. These organisms have developed ways to produce carbon based biopolymers with extraordinary characteristics that finally constitute their “bodies”. The main biopolymers that are produced by plants are cellulose and hemicellulose (carbohydrate polymers) and lignin (a 3D biopolymer of phenolic alcohols) which give wood and fibers their characteristic properties. The mechanical characteristics of wooden structures can be impressive (the highest tree currently measures 115.5m). The tensile-, compressive- and break-strength, elastic modulus and surface hardness of wood can often surpass those of conventional artificial materials and is generally of lower density [9]. However, wood produced by trees grows relatively slow. Alternatives are fast growing grasses with strong culms such as bamboo or giant reed. Plant fibers are used in modern composites and also plant seeds can produce materials with extraordinary characteristics. Although not categorized as plants, even mushrooms are used to generate modern, degradable, low energy materials (Mycobond). Whole parts or extracted fragments of those bodies have been used by human beings since thousands of years as building materials, tools or more generally as “products”.

4.2. Bamboo as exemplary experimental plant

Bamboo is a tribe (Bambuseae) within the plant family of true grasses (Poaceae) which comprises more than 1400 species [10]. 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 [11]. The culms of Dendrocallamus giganteus can grow within one growth period of a few months to full height (up to 35 m) with impressive diameters (up to 30 cm). The culms then lignify, harden and incorporate silica to extraordinary strong material [12]. 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 [13]. Lignin is responsible for the high compressive-strength of bamboo wood and cellulose for its unusual tensile- and break-strength [14]. 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 [11], [13].

This is why bamboo has received a lot of attention in material sciences.

4.3. Ecological impact of bamboo

Comparing the LCA [Fig. 6] of a current bamboo product with a conventional product made e.g. of steel or aluminium a positive impact in every single step can be detected. Furthermore near net shape grown products reduce manufacturing steps which leads to further savings in energy and thus costs.

A comprehensive environmental assessment includes water usage, fertilizer and pesticide addition, the production process, aspects of land use, (eco)toxicological implications on the environmental conditions and human health as well as the development of appropriate recycling strategies to investigate the suitability of the bio-based product as a sustainable substitution for conventional materials.

Planting bamboo requires certain environmental conditions. The main restricting factors for the cultivation of bamboo in general and to grow biomass for sustainable products in particular are the temperature with a suitable annual mean temperature of 15-20°C and a precipitation of 1000-2000 mm depending on the grown species. Furthermore the soil pH should be in a range of 4.5-7.0 [15]. Bamboo has the ability to grow on soils with a broad variety from marginal to semi-arid land [16]. Considering the long-time annual mean precipitation of North Rhine-Westphalia (Germany) of 918 mm [17] and an annual mean temperature of 9.6°C [18] bamboo seems feasible as a potential plant species for biomass production in the TEPHA project of the authors. The criticalness of the partial low temperature is currently tested with first growing bamboo plants on-site. If there is not enough precipitation irrigation of the bamboo plants, especially during shooting time in spring, it becomes necessary to ensure optimal growth conditions.

The lower annual mean temperature in comparison to the bamboo’s natural conditions could lead to decreased culm diameters and a lower biomass production of the plants. 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 irritation issue [19].

If extensive irrigation is necessary this will have negative consequences for the environment. Due to the high amount of built biomass and the high nutrient requirements, soil fertility could decrease. In addition the extent of bamboo culms harvesting requires the usage of fertilizers (NPK). In consequence the water could be polluted by fertilizers and also pesticides, which would become necessary because of reduced resistance to pests and diseases caused by intensive management like monocultures [15]. Bamboo as a fast growing and invasive plant species has moreover the potential to crowd out other plants resulting in a lower biodiversity in, e.g., bamboo forests [20].

In contrast to these negative environmental impacts cultivating bamboo has also some ecological benefits. Due to their intensive growth bamboo plants can sequester large amounts of carbon dioxide. Via long term use of bamboo products carbon could thus be fixed for a prolonged time. Furthermore bamboo plantations could decrease soil erosion for instance through their extensive root and rhizome system, as well as maintain biodiversity when providing food and habitat for insects, birds and mammals [15]. Bamboo plants are suitable to remediate polluted land. They are able to filter animal waste to prevent nitrogen effluents, to desalinate water and to remediate oil polluted lands [21]. Moreover high tolerances of Moso bamboo seedlings towards lead [22] and zinc [23] have been reported. In combination with its rapid growth the potential of bamboo as a plant for phytoremediation purposes is underlined by these findings. Due to the obtained tolerances bamboo is able to grow on degraded lands not suitable for other utilization like food production.

To assess the environmental performance of a bamboo product the whole product life should be considered (see Fig. 6). With the help of a life cycle assessment the total environmental impacts of a product can be determined “from cradle to grave”. By that all environmental burdens related to the product or service can be taken into consideration. To get a comprehensive impression of the product’s environmental performance the assessment starts investigating the used raw materials and ends with the disposal of the product [24]. While comparing the environmental performance of a bamboo substitute for a conventional product, e.g., made of steel or plastics, the most environmental friendly product worth developing further to market maturity can be identified.

To estimate the possible suitability of bamboo as a sustainable renewable resource the environmental impact of bamboo will be described exemplarily with the help of a bamboo bridge. An LCA-based calculation of environmental costs is presented for a bridge in Amsterdam (Netherlands) which is built of bamboo stem grown in Costa Rica. Environmental costs mean costs to prevent damage from the environment and are covered by the society and not the product price. The LCA complemented with environmental costs including also the product life span will be expressed in a monetary sum indicating the sustainability of the building material. Compared with steel and concrete as building material for the bridge, bamboo shows much lower values for
the environmental costs. Additionally it was figured out that nearly the whole environmental load (92,9 %) is caused by the sea transport from Costa Rica to Europe. The natural hollow design and the simple and short production process for bamboo stems promote this environmental performance. But if bamboo is laminated to rectangular products such as panels the environmental preferences will be diminished largely by addition of environmentally harmful chemicals during the production process [25]. In principle these results suggest the suitability of bamboo culms as an environmental friendly building material, especially if it is used in countries where it is grown.

4.4. Experimental procedure

For the mentioned advantages in 4.2 and 4.3 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 feasible to being produced, it will be possible to predict what kind of whole products or semi-finished products are contrivable. In further experiments different species will be tested.

As bamboo needs approximately three years to totally lignify, structural testing on the influenced plants cannot be done in the near future. But until then naturally grown bamboo sticks from the same retailer that have had similar growing conditions are used for the different testing scenarios. This offers a good basis to compare the characteristics with the influenced plants’ data once they are fully lignified and tested structurally.

5. Discussion and Outlook

This contribution introduces a novel approach to evaluate the potential of substituting conventional materials and manufacturing processes through manipulated, reproducible growth of plants. The multidisciplinary consortium has teamed up to identify and assess the technical, ecological and economic feasibility of this approach. First results and data sets for selected plants have been developed to start building a broad database of natural materials and corresponding technical functions for different disciplines.

Once this database is set up to a certain completeness with analysis even on the plant cell level, naturally grown multi-material structures and their synthesis will be considered. Another aim of the authors is to develop design guidelines for the use of TEPHA-materials.

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