INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

SUBSTITUTING CONVENTIONAL MATERIALS AND MANUFACTURING FOR SUSTAINABLE, NEAR NET SHAPE GROWN COMPONENTS

Löwer, Manuel; Beger, Anna-Lena; Feldhusen, Jörg; Wormit, Alexandra; Prell, Jürgen; Usadel, Björn; Seiler, Thomas-Benjamin; Kämpfer, Christoph; Hollert, Henner; Moser, Franziska; Trautz, Martin
RWTH Aachen University, Germany

Abstract

Society's demand for ecologically produced and sustainably operable goods is a key driver to substitute conventional substances such as metals or plastics. Most of today's eco-design approaches are limited to the selection of the right material and the industrial processing, to manufacture the desired design. The authors of this work are scientists from the areas of cell-biology, eco-toxicology, engineering- and industrial-design, and teamed up to use directed natural growth of bio-materials. The aim is to minimize conventional production steps and decrease the amount of resources needed for manufacturing. In the first step the team categorizes and analyzes potential plants. In addition, requirements for different sorts of products are defined. Matching parts of both databases are identified. The aim of this research is to give an overview of possible function-plant relations of near net shape grown materials. Single materials as well as composites are taken into account. Eco-investigations include the whole Life Cycle Assessment. Additionally mechanical properties, design restrictions and surface quality are examined as major issues for sustainable, safe and sound products.

Keywords: Sustainability, Technical Product Harvesting, Grown Components, Eco Manufacturing, Industrial design

Contact:
Anna-Lena Beger
RWTH Aachen University
Chair and Institute for Engineering Design (ikt)
Germany
beger@ikt.rwth-aachen.de

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

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 analyse 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 analysing 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 eco-balance 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 which enables 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, eco-toxicologists, structural-, engineering- and industrial designers are currently working on this task to develop the Technical Product Harvesting (TEPHA). 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 for the substitution of a conventional product by a product made of renewable resources that have preferably grown near net shaped? To answer this question 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 solutions, the engineering methodology according to Pahl and Beitz is taken as a systematic basis (Pahl et al, 2013). 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 analysed and then categorized and clustered. This outcome as the basis for the resulting data base comprises information about their basic functions and required mechanical, geometrical and material/substantial properties. At the same time data about possible plants and organisms is collected and systematically structured. The data is analysed to find matching features that allow biological ways to reproduce the required technical properties (Figure 1).

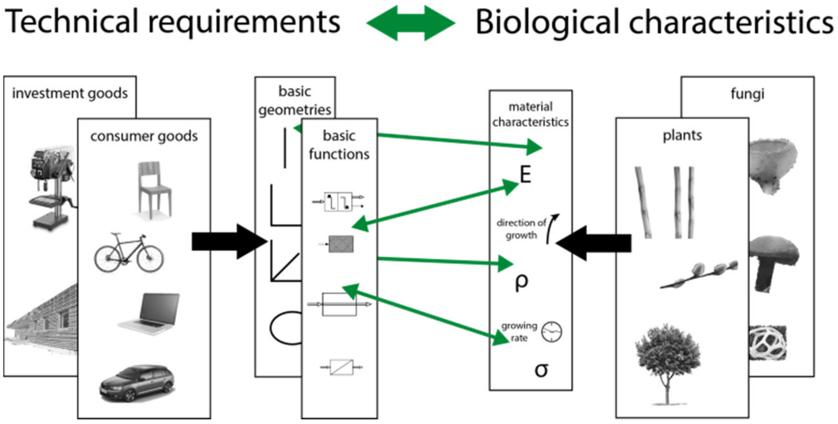

Figure 1. Systematic approach to match technical requirements with biological characteristics

The main focus here is to find processes with little environmental impact that are able to generate reproducible goods. This may start with substituting a conventional material like steel or plastic by a renewable material like wood. One step ahead would be to influence the shape of an organism in its growth and use near net-shape grown plants and take advantage of a natural topology optimized shape and of saving manufacturing steps. Bringing that even further could lead to influencing the cell structure of certain organisms in order to modify their growths, shape and structural behaviour.

In the first stage of the experiments it is analysed to what extent it is possible to influence the growth of a living plant in terms of imposing it into wanted directions and shapes. This is exemplarily tested on one specific plant whose 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.

In addition to mainly functional properties the ecological aspect as well the semantic benefit of natural materials are discussed. Economical aspects will also be listed.

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

2.2 Current applications of organisms for technical purposes

The majority of technical products made of renewable resources have been made of relatively naturally grown plants that have been altered in a manufacturing process to create their required net shape. Either the original solid state with external connecting elements, single fibres or cells in a composite or biomass such as starch for biodegradable plastics have been utilized for different kind of products. (Figure 2)

Figure 2. (a) Frame made of bamboo canes (Bauer, 2014)
(b) Snowboard made of laminated bamboo (Schwabe, 2014)
(c) packaging material made of corn starch (Ambalaj, 2014)

The use of natural materials grown in shape as design objects has also been introduced by several artists. One of the most known artefacts is the so called "chair farm" by Werner Aisslinger. The aim of his installation (Figure 3) is to indicate the change in consumer behaviour to a more regional and sustainable demand.

But still growing plants and their characteristic shapes have mainly been used as unique artefacts or design objects. The "Pooktre Living Chair" or the new field of botanical construction (German: "Baubotanik", estbl. 2007 by Prof. Dr. Gerd de Bruyn, Stuttgart) (Figure 3) are well known examples.

Figure 3. (a) Chair Farm" by Aisslinger (Aisslinger, 2012)
(b) Chair made of a living tree (Cook, 2014)
(c) Handrail of a bridge (Moto, 2014).

Another current research field is the biomimetic where natural systems are imitated for technical purposes. Copying the topology and its functionality is the main issue here. Whereas the material that is being used can be either a conventional or natural material.

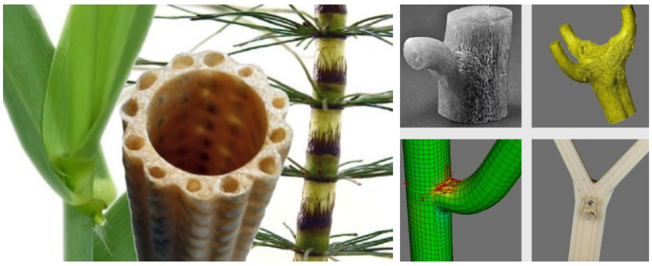

Figure 4. (a) Technical Plant Stem as fibrous compound material, inspired by biological templates (Speck, 2014) (b) Technical structures inspired by the growth of plants (DBU, 2014)

Only one major project could be so far identified where the shape of a living plant was modified and used for technical purposes. 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. They could show that it was possible to manipulate the shape of the cross section as well as the bending of the cane.

Figure 5. Bamboo shape modification over substructures (Vittouris, 2011)

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

Additionally the authors work focusses on the natural limits when manipulating the growth of a plant. Furthermore the structural behaviour is analysed. In particular the structural difference and strength between 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 analyse the potential of manipulating 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, too. Its main biological, technical and ecological properties plus current applications are introduced in section 4. Bamboo is chosen here as a first example. The way it is presented in this work needs to seen exemplarily. The aim of the project is to investigate numerous species of plants in a similar way.

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. 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, (ISO 1445, 2012), (ISO 14040, 2006), Figure 6.

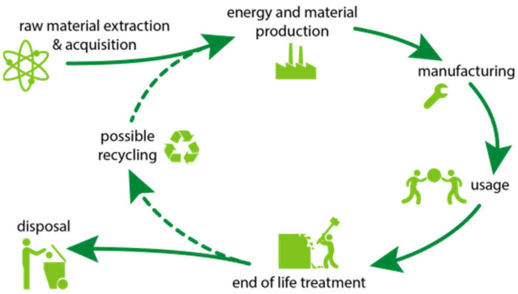

Figure 6. Life Cycle Assessment (LCA)

3 DESIGN METHODOLOGY

3.1 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” (Pahl et al, 2013). 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.

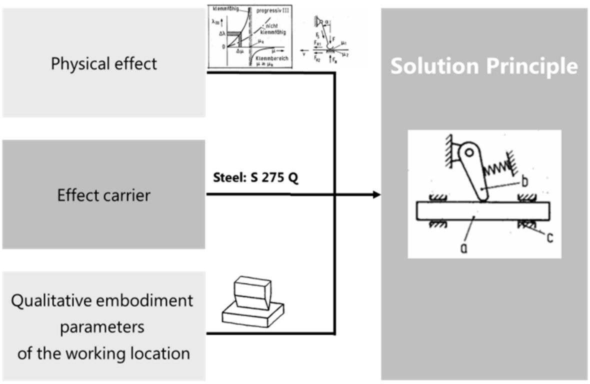

Figure 7. Elements of Principle Solutions (Pahl et al, 2013)

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 (Koller, 1998) 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. Next to this it will also contain quantitative data on the LCA (4.3) as well as semantic characteristics (3.2) 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 that 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 1). Along with the evaluation of the fulfilment of the technical functions, ecological as well as semantical criteria will be displayed. Ideally the user will then have the choice of different material 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 (Koller, 1998), 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 (see section 5).

3.2 Semantics of natural materials

Even though installations made of organic material (Figure 3) are mainly single handcrafted objects and no mass produced articles, they address 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 found in natural materials.

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. In this case, we talk about artwork (Figure 8). Altschuller states that real life products i.e. physically existing items are subject to sensory perception and carry semantic functions (Altschuller, 1998).

The authors therefore see a great potential in using natural resources for consumer goods. The semantic and haptic feeling will help the responsible consumer to identify himself with the product he is using.

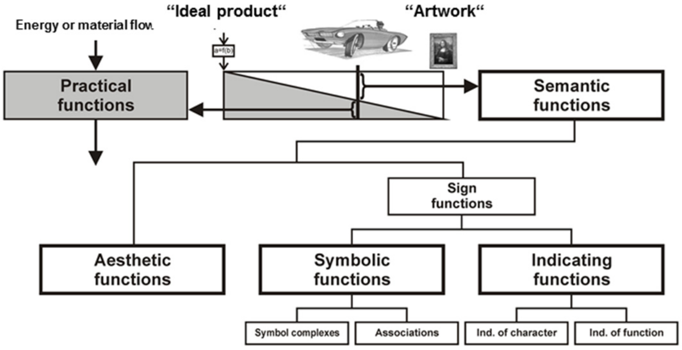

Figure 8. Integrated Product Model (Brezing, 2006)

4 BIOLOGICAL CHARACTERISTICS

4.1 Biological Background

Plants are photoautotrophic organisms that use the energy of sunlight to convert atmospheric CO_2 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 fibres 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 (Rijsdijk, 1994). However, wood produced by trees grows relatively slow. Alternatives are fast growing grasses with strong culms such as bamboo or giant reed. Plant fibres are used in modern composites and also plant seeds can produce materials with extraordinary mechanical 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 (Poacea) which comprises more than 1400 species (Kelchner, 2013). 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 (Farrelly, 1984). 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 (Janssen, 1991). 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 (Rottke, 2002). Lignin is responsible for the high compressive-strength of bamboo wood and cellulose for its unusual tensile- and break-strength (Liese, 1998). 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 (Farrelly, 1984), (Rottke, 2002).

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

4.3 Ecological impact of bamboo

Comparing the LCA (Figure 6) of a current bamboo product with a conventional product made e.g. of steel or aluminum 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 (Song, 2011). Bamboo has the ability to grow on soils with a broad variety from marginal to semi-arid land (Zhou, 2005). Considering the long-time annual mean precipitation of North Rhine-Westphalia (Germany) of 918 mm and an annual mean temperature of 9,6°C bamboo seems feasible as a potential plant species for biomass production in the TEPHA project of the authors (LANUV NRW, 2014). 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 irrigation issue (Lewis, 2007).

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. 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 (Song, 2001). 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 (Huston, 2003).

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 fixated 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 (Song, 2001). 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 (Ogunwusi, 2012). Moreover high tolerances of Moso bamboo seedlings towards lead (Liu, 2014) and zinc (Liu, 2014) 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 (Figure 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 products environmental performance the assessment starts investigating the used raw materials and ends with the disposal of the product (Klöpffer, 1997). 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 (van der Lugt et al, 2006). 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.

5 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 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 9). In the In further experiments different species of bamboo and other plants and fungi will be tested.

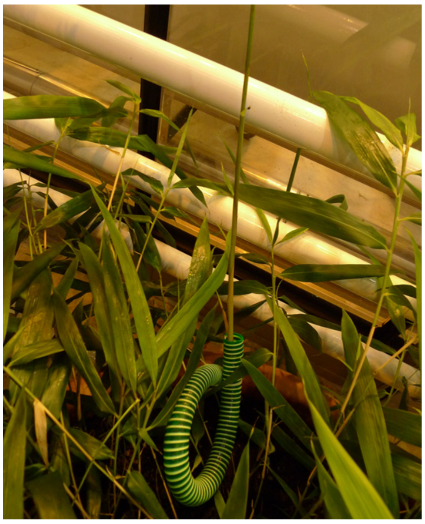

Figure 9. Bamboo growing in a loop trough a tube

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 to find out structural behaviour. This offers a good basis to compare the characteristics with the influenced plants' data once they are fully lignified and tested structurally.

To get a better understanding of the structural potential of bamboo that has grown near net shaped it is further planned to simulate the plant in a finite element analysis (FEA). The comparison with experimental determined material data from plants that have been forced into its shape after it has been cut will allow an estimation of the structurally gained quality. Along with the simulation a cell-analysis of the two different kinds of manipulated bamboo stems will be done. Since the simulation of bio material naturally entails a certain deviation this duplication will serve as a proof.

6 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 and fungi as either single materials or mated with natural resins for multi-material systems. The multidisciplinary consortium has teamed up to identify and assess the technical, ecological, semantical and economical 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. Further experimental as well as simulative investigations on different plants and organisms are planned to supply a wide range of data.

Once this database is set up to a certain extent, analysis even on the plant cell level, naturally grown multi-material structures and their synthesis will be considered.

All gathered information will deliver input to develop design guidelines for the use of TEPHA-materials.

REFERENCES

Aisslinger, B. (2014) http://www.aisslinger.de.
Altschuller, G. (1998) Erfinden – Wege zur Lösung technischer Probleme. Berlin: Verlag Technik.
Ambalaj, K., (2014) http://ambalaj.se/.
Bauer, G. (2014) http://pedelec-elektro-fahrrad.de/.
Brezing, A. (2006) Merging up-todate approaches of engineering design and industrial design theory into an integrated interdisciplinary design theory/Planung innovativer Produkte unter Nutzung von Design und Ingenieurdienstleistung. Schriftenreihe Produktentwicklung und Konstruktionsmethodik. Aachen: Shaker.
Cook, P. (2014), http://pooktre.com/.
DBU (2014) Deutsche Bundesstiftung für Umwelt, http://www.dbu.de.

Environmental management Eco-efficiency assessment of product systems. Principles, requirements and guidelines (ISO 14045:2012). (2012).

Environmental management Life cycle assessment – Principles and framework (ISO 14040:2006). (2006)

Farrelly, D. (1984) The Book of Bamboo. Sierra Club Books.

Huston, M. A, Marland, G. (2003) Carbon management and biodiversity. J Environ Manage; 67: 77-86.

Janssen, JJA. (1991) Mechanical properties of bamboo. University of Eindhoven, NL.

Kelchner SA, Bamboo Phylogeny Group. (2013) Higher level phylogenetic relationships within the bamboos (Poaceae: Bambusoideae) based on five plastid markers. Mol Phylogenet Evol. 67(2):404-13.

Klöpffer W. (1997) Life Cycle Assessment – From Beginning to the Curent State. Environ Sci & Pollut Res; 4(4): 223-228.

Koller, R. (1998) Konstruktionslehre für den Maschinenbau: Grundlagen zur Neu- und Weiterentwicklung technischer Produkte mit Beispielen. Berlin: Springer.

LANUV NRW (2014), Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen; http://www.klimaatlas.nrw.de/ site/nav2/Niederschlag.aspx?P=2, http://www.klimaatlas.nrw.de/ site/nav2/ Temperatur.aspx?P=2

Lewis, D, Miles C. (2007) Farming Bamboo. 1 ed. Raleigh: Lulu Press.

Liese, W. (1998) The anatomy of bamboo culms. International Network of Bamboo and Rattan.

Liu, D. et al. (2014) Lead accumulation and tolerance of Moso bamboo (Phyllostachys pubescens) seedlings: applications of phytoremediation. J Zhejiang Univ-Sci B (Biomed & Biotechnol); in press.

Liu, D. et al. (2014) Effect of Zn toxicity on root morphology, ultrastructure, and the ability to accumulate Zn in Moso bamboo (Phyllostachys pubescens). Environ Sci Pollut Res.

van der Lugt, P. et al. (2006) An environmental, economic and practical assessment of bamboo as a building material for supporting structures. Construct Build Mater; 20(9): 648–56.

Matthiesen, S., (2002) A contribution to the basis definition of the element model “Working Surface Pairs & Channel and Support Structures” about the correlation between layout and function of technical systems. Forschungsberichte Inst. Für Maschinenkonstruktionslehre und Kraftfahrzeugbau, Universität Karlsruhe.

Moro, C. (2012) http://www.magazin.bilfinger.com

Ogunwusi, A. A, Jolaoso M. A. (2012) Bamboo, conservation of environment and sustainable development in Nigeria. Advances in Arts, Social Sciences and Education Research; 2(9): 346-358.

Pahl G., Beitz W., Feldhusen J., Grote K.-H. (2013) Konstruktionslehre. 8th Edition Berlin: Springer.

Rijsdijk, J. F., Laming P. B. (1994) Physical and related properties of 145 timbers. Kluwer, Dordrecht, Boston, London.

Rottke, E., (2002) Mechanical Properties of Bamboo. RWTH Aachen University. Faculty of Architecture. Aachen, Sect. 3, page 11; Sect. 4, page 11.

Schwabe, T. (2012) http://www.indigosnow.de/.

Song, X. et al. Carbon sequestration by Chinese bamboo forests and their ecological benefits: assessment of potential, problems, and future challenges. Environ Rev 2011; 19: 418-428.

Speck, Olga; Kompetenznetz Biomimetik (2014), http://www.bionik-bw.de/.

Vittouris, A., Richardson M. (2011) Australasian Transport Research Forum 2011 Proceedings. Adelaide, Australia

Zhou, B.-Z. et al. (2005) Ecological functions of bamboo forest: Research and Application. J For Res; 16(2): 143-147.

ACKNOWLEDGEMENTS

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