# HIERARCHICAL DESIGN AS A TOOL IN DEVELOPMENT OF WOOD-BASED COMPOSITE APPLICATIONS

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## ABSTRACT

Traditionally new materials have been developed in order to solve technological problems within the aerospace, military or medicine fields. Renewable materials are developed from another perspective; they are developed in order to meet the demands from a sustainable society. If they are developed to become replacement materials, they have to be better or cheaper in order to take market shares or there has to be a political willingness to promote them. Economical subsidies are never sound and a better strategy to introduce these new materials is to identify their unique properties and possibilities and to market them. One such strategy, materials design, will be discussed in this paper.

Renewable materials open for new strategies in design. Traditionally, in the life-cycle analysis (LCA) perspective materials should be recycled as materials and preferably as the original material quality. This implies that there has to be a limited number of materials and they need to be identifiable in order to be sorted. Renewable, natural fibre reinforced materials will degrade during recycling. The consequence of this is that these materials should better be recycled as energy. An integrated materials and product design will therefore be a new sustainable strategy.

Researchers involved in R&D, i.e. research and development, of new materials have been involved in discussions and collaborations with the R&D department of companies producing and marketing materials. In parallel, industrial designers and engineers involved in product development and design have had on-going discussion with the same companies, but through their marketing department. This means that there is generally no communication between R&D and end-product designers. This paper suggests an R&D*&D* concept, Research and Development and Design, a hierarchical, integrated materials and product design strategy.

## 1. BACKGROUND

Forest based renewable composites are traditionally looked upon as sustainable replacements for existing oil-based materials. This leads to the situation where the new materials have to be cheaper and better in order to take market shares (cf. e.g. [1]). Legislation and other political decisions can help the introduction, but it is never good to have artificial aid to make a material choice economically viable. A catch 22 situation exists where huge volumes are required in order to get a low production cost and no-one is willing to put the first order as long as the price is high. Hence, it is important to find new applications and to market unique materials properties that can be marketed at a higher cost in smaller volumes in order to reach the market. One strategy to get from *technology push* to *market pull* is coupling design to materials development; let R&D stand for *Research and Design*!

Materials development has historically been technology driven by the aerospace, medicine and defence industries. Some examples are high-tech applications like spare parts for the human body, bullet-proof outfits for soldiers, super-performing low-weight high-tech materials for astronauts, small volume materials but very high value and necessary for the solution of an important problem. Renewable materials are not developed in order to solve a high-tech problem. The driving force is the sustainable society, the willingness not to consume more than what earth can produce per year. Today we consume more than earth produces every year and in 2006, we passed the “ecological debt day” [2], i.e. October 9. This marks the date that the planet’s environmental resource flow goes into the red and we begin operating on a non-existent environmental overdraft.

Figure 1 shows a schematic of how the price per weight for a material depends upon the volume for a material (or a product). Renewable materials should not be introduced at the lowest point of the curve. In marketing of these new materials, unique properties is a possible approach.

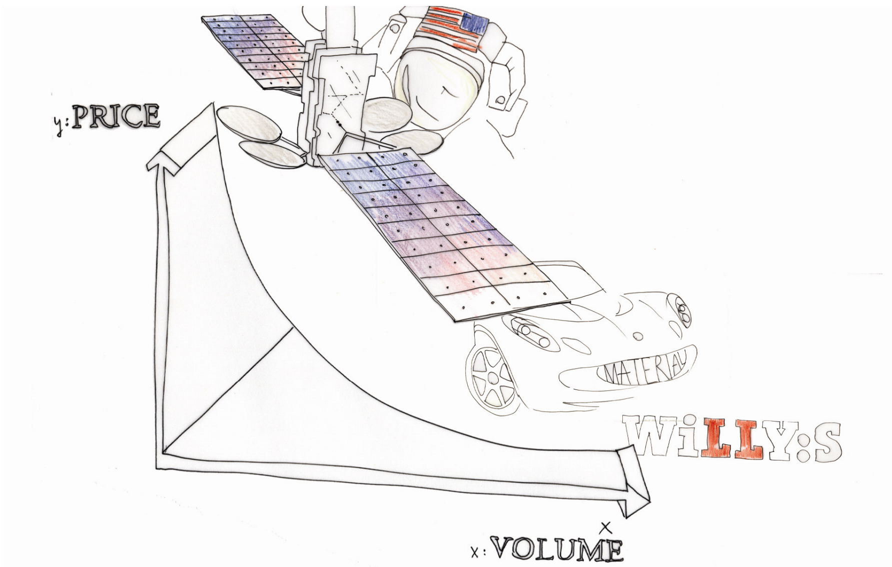


Figure 1: Price vs. volume for materials. Over time materials evolve from high-tech specialities to commodities. Drawing Farvash Razavi and Nandi Nobell

The European Council has decided that new cars should be designed so that 95% of the car (from 2015) should be recyclable and 85 % of the weight of the car should be recycled as materials, if possible parts should also be re-used, there are a number of details that are specified and that cannot be reuse due to safety or environmental aspects. Energy recycling is becoming acceptable, especially if the starting material is renewable [3].

In LCA, reuse is the highest form of recycling, followed by materials recycling as identical material, the two lowest forms has been energy reuse and composting. Energy reuse is being re-evaluated when it comes to renewable materials, as they will be a part of the renewable energy quota.

Materials are generally degraded during recycling, see Figure 2, and renewable fibre reinforced composites in special and hence they should be recycled as energy. This opens the possibility for freedom in the materials design. There will not be a limitation on how many materials and how these will be collected and sorted. There will be only one system for renewable materials to be recycled as energy. This means full freedom to use different proportions reinforcement vs. matrix, different types of fibres, wood, agricultural or regenerated fibres can be used in different states of modification as long as all ingredients are renewable and the extraction/production processes follow sustainability criteria. The same is valid for the choice of matrix materials and performance chemicals that might be used. Furthermore the products will be collected in the same fraction independent upon how they have been produced, thermosets or thermoplastics, extruded, injection moulded or hot pressed is irrelevant.

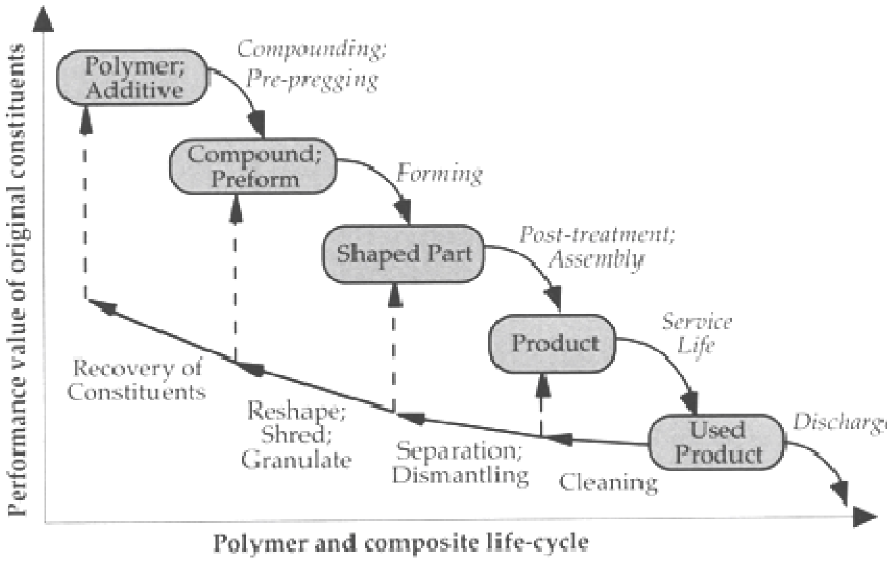


Figure 2. Performance value of polymers and composites throughout their life cycle [4].

One of the most important factors in sustainability assessment and eco-design is to reduce the amount of materials and energy used in a product and during its processing. Recycling as energy opens for the possible tailoring of materials in order to optimize the amount needed in a certain application.

## 2. DESIGN HIERARCHIES

The materials properties needed in order to give a specified products relevant engineering properties is determined in the product design step. The materials properties of a material depends upon structural features, which are depending upon which fibre quality has been chosen, what kind of fibre orientation, which matrix has been used, the interface between fibre and matrix and which composite process have been chosen.

The fibre properties are in their turn species specific and depend upon extraction process, chosen surface and/or fibre wall modifications etc. A top-down strategy to materials design of structures composed of different materials with regard to fracture and failure has been proposed by e.g. Hutchinson and Evans [5].

There is an intense on-going development within the field of renewable composites based upon cellulose reinforcement elements from the forest. Materials development and design are closely tied together with fundamental research on ultra-structural level of wood fibres, e.g. [6], and micromechanics of wood fibre composites, e.g. [7]. Studies of failure mechanisms coupled with extensive knowledge on the cellulose fibre and the chemistry of the interface between matrix and fibre surface has made it possible to calculate how structural features of the fibre contribute to final materials properties. Integrated product and materials design can be structured into three different levels:

The hierarchical design concept constitutes of design on three different levels:

- Component design (materials' components)
- Materials design or composite design
- Product design

*Component design* – This is where the different components or constituents in the material are designed. Fibrils and fibres are tailored to have given chemical and structural features. Examples of renewable and degradable components from the forestry and agricultural sectors are microfibrillar cellulose, hemicellulose, lignin, polylactide and starch. Researchers working on this design level typically have backgrounds in chemistry and chemical engineering.

On the *component level*, the fibre is "designed", in this case there are some properties that are species specific, such as fibre length and with. Another fibre property is the fibre wall thickness, which controls if the fibre will stay circular and tube-shaped or collapse into a more flexible band. Fibre wall thickness depends upon if it is early wood or late wood fibres. In a tree, these different fibres can be observed as annual rings, but with modern techniques, like cyclones, it is possible to fractionate and separate these fibre types. These fibres have been observed to contribute differently to the stiffness of composite materials [8]. The composition of the fibre changes with the extraction process, a thermo-mechanically liberated fibre, thermo-mechanical pulp (TMP), is produced with up to 95% yield and contains cellulose, hemicellulose and lignin together with minor amounts of extracts. There are different chemical pulping processes, like sulphite or sulphate resulting in different chemical composition. The extracted fibres can be bleached to different degrees and a fully bleached sulphite pulp fibre constitutes almost only cellulose and the total yield is around 40%. If lignin is present, the fibre will be less hydrophilic and more compatible with lipophilic polymers. The fibre surface can also be modified using different techniques, from surface active agents and multilayer treatments. It is also possible to crosslink the fibre wall, which makes it less prone to swelling. The effect of various fibre treatments on the mechanical properties of composites has been studied by Neagu et al. [9]. There are also many different plastics, mixtures of polymers and performance chemicals to choose between and to modify, melting point, glass transition temperature etc depend upon the degree of polymerisation, which is the chain length of the polymer. The polymer can be chosen to easily crystallize or to stay amorphous. Different additives can also be designed and added in order to give a controlled interface between the polymer and the fibre, to act as softener or make the final material fire resistant, etc. Component properties will affect the engineering properties in the final product.

*Composite design* – This is where the material used is given its final structure: What kind of fibres? How much fibres and how should they be oriented? What kind of production process should be used? This level incorporates micromechanics to establish useful microstructure-property relations, which can be used for simulations to identify key microstructural features for rational materials development with improved engineering properties. This goes hand in hand with development and tuning the processing methods, which control the resulting microstructure. The traditional background is mechanical engineering and materials science.

*Product design* – This is where macroscopic structural elements are used to give the product the desired properties. This level benchmarks back on the two previous levels. Properties needed in the end-product require a given set of properties on the material and component levels. At the governing product level, not only quantitative scientific or engineering properties are considered, but also qualitative and more subjective properties such as appearance, aesthetics and function etc. Typical backgrounds are engineering-oriented computer-aided design and artistically-oriented industrial design.

On the *product design level*, the designer will have the freedom to optimize hers/ his design to reduce the materials consumption. The designer will not have to choose the existing material and adapt the design to a given materials limiting properties and how it can be sorted and recycled. There will of course be limitations upon which properties that can be achieve in a sustainable, renewable fashion also, but there will be quite a wide span of engineering properties.

The whole system is built upon controlled design on the three levels coupled through working micromechanical models and calculations. Furthermore, a lot of the on-going materials development is performed within one single level. Results from the component level can only be utilized by the pulp and paper industry leading to improved qualities of already existing concepts. If the pulp industry wants to find new markets for the fibres, they have to collaborate with chemistry, polymer and composites manufacturing industries. Thus, by regarding the three-level system interdependently, in contrast to separate disciplinary entities, the integrated approach facilitates sustainable product development. The integrated design process necessitates multidisciplinary collaboration, which in turn requires an efficient interface between design levels over which effortless communication can take place. Since the training and education of the scientist, engineers and designers at the different design levels are entirely different, the first hurdles to overcome are to break down the linguistic barriers, and to achieve mutual understanding of the principles, tools and goals.

## 3. INTEGRATED MATERIALS AND PRODUCT DESIGN

An understanding of how engineering properties depend upon structural elements and component composition requires a good understanding and advanced micromechanical models. How the ultrastructure of the fibre wall affects fibre properties is research project within the Wood Ultrastructure Research Centre (WURC) and the New Materials & Composites Group at STFI-Packforsk is engaged in micromechanical modelling trying to link engineering properties back to how individual fibres contribute [6, 10]. The building of models and coupling to LCA and sustainability assessment are important tools in the integrated materials and product design toolbox. Through the creation of a meeting place and a common language for scientists and designers we want to create the R&D&D relation (last D indicates 'design'), that will help to get new materials from technology push to market pull.

The project "Integrated Materials and Product Design" involves the Departments of Fibre and Polymer Technology and Solid mechanics at the Royal Institute of technology, KTH, in Stockholm, Industrial Design and Furniture and Interior Design at Konstfack, University College of Arts, Crafts and Design, Stockholm, Division of Polymer Engineering at Luleå University of Technology, Luleå, Sweden, and STFI-Packforsk AB, Stockholm.

## 4. AN EXAMPLE – THE 'KOFES'

In this presentation, an example will illustrate our experiences in linking the different design levels into an integrated scheme. Within the New Materials & Composites Group at STFI-Packforsk, we have been working on the development of renewable fibre reinforced composites since 1999, and in an attempt to market our findings and reach to the market, two designers were employed and asked to design a materials sample that could be sent to design managers in the industry. The sample should not give any associations on how it the material could be used, just show the possibilities with the material concept and the chosen production method, in this case moulding. A restraint was given, the sample should fit into an envelope in order to allow distribution via mail. The sample was named 'kofes' after a short story by the Swedish author Birger Vikström [11]. Samples have been sent to design managers at different European companies and a number of new projects have resulted from this. It has also been displayed at the Milan Mobile fair April 2007.

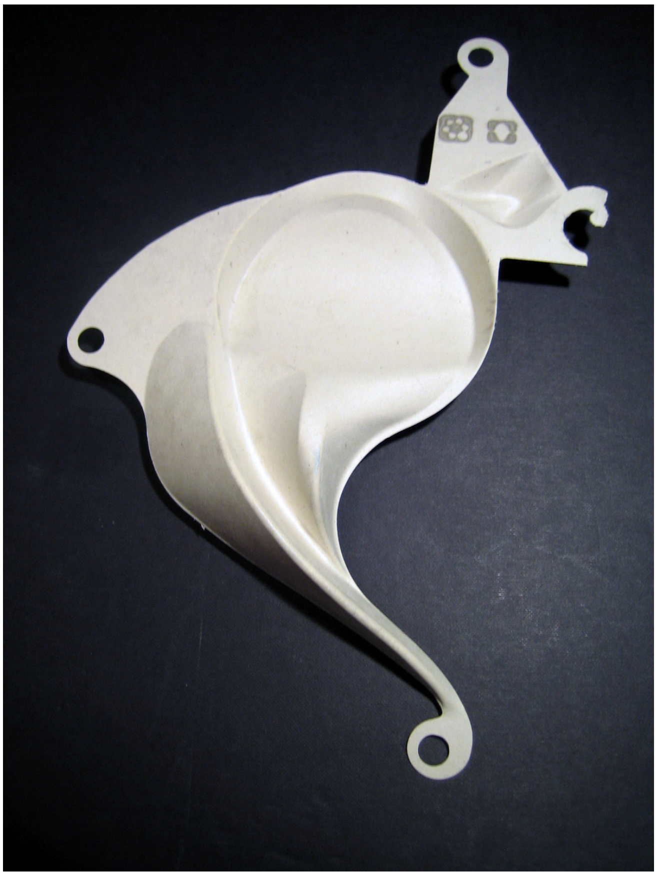

Figure 3: A 'kofes' moulded in 75% CTMP pulp fibre and 25% PLA. The material is fully renewable. Design: Farvash Razavi and Nandi Nobell.

The 'kofes' signifies a goods sample that should show many different application possibilities and properties without limiting the creativity by association to specific products [12], i.e. *product design*. Concomitantly, processing techniques have been refined and the microstructure has been tailored on the *composite design* level to meet the demands of the end product. This included development of wet-forming techniques for commingled fibre-mats followed by hot-pressing to mould three-dimensionally shaped composite parts. To achieve processable fibre mats, which meet the demands on the properties of the composite materials and of the final product, the fibres themselves has been chemically modified for increased stiffness dimensional stability, i.e. *component design*.

## ACKNOWLEDGEMENTS

The authors wish to thank Farvash Razavi (Konstfack, University College of Arts, Crafts and Design) and Nandi Nobell (Central Saint Martins College of Art and Design) for all their efforts in the design and manufacture of the 'kofes'. Financial support has been received from the Swedish Governmental Agency for Innovation Systems (VINNOVA) under contract number 2004-01560 for the project "Wet-processing of Biocomposites for 3D Shell Applications", and from participating industries Alfa Laval, Stora-Enso, Södra Cell, Billerud, Korsnäs-Frövi, Mondi-Packaging, Br. Hartmann A/S, M-Real and BASF within the research cluster 'New Fibres New Materials'.

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