Adding value to natural fiber reinforced materials by means of product design and development

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Abstract

The environmental awareness has been a trend topic during the last years. In the field of composite materials research derived in the interest for the use of fibers obtained from renewable sources as reinforcement for composite materials. Undoubtedly a good material without use lacks value. In the present work the composite materials and the product design and innovation groups of the University of Girona worked together to valorize a natural fiber based composite to create a new product, in a multidisciplinary process that involved designers, chemists and engineers. The addition of natural fibers allowed the creation of environmentally friendly materials.
The starting point was a formulated and mechanically characterized composite material, meaning that we know its tensile strength, Young's modulus… The material, using wood fibers as reinforcement, was proposed as a candidate to replace fiberglass based composites (less environmentally friendly than natural fibers). We designed a new proposal for an outdoors bench. The design was based on a specification list derived from a market analysis. During the process different creativity techniques were used. Once it was designed the concept was modelled and calculated by means of Computer Aided Engineering software, subjecting the bench to the expected loads and boundary conditions. The result was a proposal of a new outdoors bench fabricated with an environmentally friendly material.

1 Introduction

Product design adds value in many different ways. For instance: new features, better use, adding new technologies, with an enhanced aesthetic, reducing the Price and widening the customer's scope, or by changing materials and processes. The present work presents the development of a new product with a multidisciplinary approach. The design of an outdoors bench, allowed the value creation by the adoption of new environmentally friendly materials, specifically, a composite material reinforced with Wood fibers. To fulfil the objective it was necessary the involvement of practitioners and experts in different fields of knowledge, specifically, materials sciences, industrial design and product engineering. The phases of the project were not sealed allowing the continuous collaboration of all the actors. The constant communication and the focus on the detail allowed incremental and continuous improvements on the quality of the outcomes. This required the use of a common language that allowed the transfer of information without losses between all the practitioners and experts.

The idea started from the presentation a new composite material from the material sciences experts. That composite material was more environmentally friendly that the polymeric materials commonly used to manufacture outdoors urban furniture. The product designers are able to understand the market needs and develop new product concepts. Those products will incorporate functional and emotional feature, embodied as a geometrical definition.

The role of the product engineers was to perform all the required calculations that ensured the safety and feasibility of the product. They had a limited freedom to change the geometry without changing the character of the product. The changes responded to manufacturing processes requirements and making sure that the use requirements were achieved. The output was a new model that introduced all the parameters need to allow the manufacture of the product. The product was safe and feasible. The last milestone was the study of the technical, economic and market feasibility of the product. It was simulated three steps design process (fig.1) that simultaneously managed and shared the information of every stage to give feedback from one phase to the next.

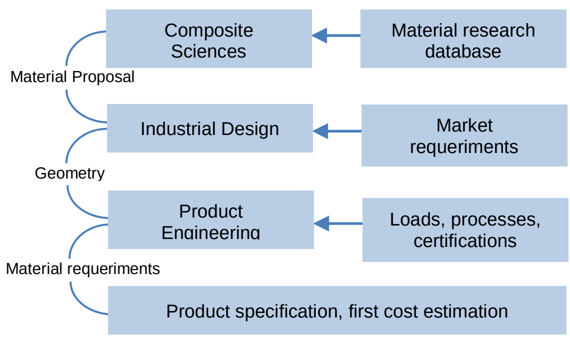

Fig. 1 Research framework

The output of the whole process was a concept of a new product manufactured with a new material with value added features thanks to product design, and with its legal and technical feasibility ensured by means of product engineering. The final product was highly differentiated from its competitors. Hence the new process had a multidisciplinary approach that proved valuable.

2 Materials and methods

2.1 Materials

Stone groundwood pulp (SGW) is a fibrous material, commonly prepared from softwood, in a process that can reach 98.5 wt% yields. The most common applications of SGW are in the production of printing papers, news print, boards, and packaging papers. Stone groundwood pulp is frequently used in paper formulations together with mechanical pulp and recycled fibers. Thanks to these applications, the existence of stone groundwood in the global market is guaranteed. Moreover, due to its fibrous morphology, stone groundwood can also find application as a reinforcing element of polymer matrices such as polypropylene or polyethylene [1-3] composite materials.

Polypropylene Isplen PP090 G2M (PP) provided by Repsol-YPF (Tarragona, Spain) was used as a polymer matrix. This polymer had a medium-high melt flow index focused for injection-moulding purposes. Stone ground wood (type PX2), derived from pine (Pinus radiata), was supplied by Zubialde S.A. (Aizranazabal-Guipúzcoa, Spain) and was applied for reinforcing PP. Maleated polypropylene MAH–PP Epolene G 3015 from Eastman España (Las Rozas, Spain), S.L., with an acid number of 15 mg of KOH/g and a molecular weight of 24.800 Da, was used as a coupling agent.

2.2 Methods

The composite was prepared by the addition of the polymer matrix and the reinforcement inside a Brabender plastograph internal mixer (Duisburg, Germany). Composites comprising 10 to 30 wt% were prepared with both fiberglass and stone ground wood reinforcements. The coupled-composites were obtained by adding 6 wt/wt% of MAH–PP with respect to the fiber content. The mixing procedure was carried out at 180 ºC at 80 rpm for 8 min. The obtained composites were pelletized by using an Agrimsa pelletizer (Sant Adrià de Besós, Spain). The pellets were dehumidified with an oven at 80ºC for 24 hours.

The samples for the tensile test were produced with a steel mould in an injection-moulding machine (Meteor 40, Mateu & Solé). Ten test specimens from each obtained composite blend were used for the experiment. The processing temperatures were 175, 175, and 190ºC (the machine has three heating areas), the last corresponding to the injection nozzle. First and second pressures were 120 and 37.5 kgf/cm2, respectively. Standard composite specimen samples (approx. 160x13.3x3.2mm) were obtained and used to measure the tensile properties in agreement with ASTM D638.

Prior to the mechanical testing, the specimens were stored in a Dycometal conditioning chamber at 23ºC and 50% relative humidity during 48 h, in agreement with ASTM D638. Afterwards, composites were assayed in a Universal testing machine (InstronTM 1122), fitted with a 5kN load cell and operating at a rate of 2 mm/min. Tensile properties were analysed by means of dog-bone specimens, according to ASTM D638 standard. Results were obtained from the average of at least 5 samples.

2.3 Industrial Design and Product Engineering

The product was designed using traditional monochrome techniques such as: technical analysis, functional, use, formal aesthetic and market. Braindrawing, Zwicky box, and SCAMPER were used as creative techniques. Product concept was started from some initial ideas that were analysed, discussed and refined during the whole process. The three-dimensional prototype and the analysis of the bench were developed with a CAD/CAE platform, SOLIDWORKS, by Dassault Systemes.

3 Results and discussion

3.1 Composite material selection

The common materials that are used for the production of these types of products are fiberglass/Polypropylene (PP) reinforced composites. Both PP and fiberglass (FG) are easily accessible. However, fiberglass includes some disadvantages, such as its huge energy cost production, its detrimental effects on health, and its abrasiveness toward machinery; the end of its life cycle generates big quantities of solid residue. Technical alternatives to fiberglass can be found in the use of stone ground wood (SGW) [4]. SGW is the raw material for the production of newspaper sheets and packaging boards, so it is already available in the market, in contrast to some other cellulosic fibers. The properties of polypropylene composites reinforced with fiberglass were compared to those that were reinforced with stone ground wood, and its suitability was analysed in the view of the production of an outdoors bench.

Reinforcement (wt%)	Sized-fiberglass composites		
	σ_t^c (MPa)	E_t^c (GPa)	ε_t^c (%)
0	27.6 (0.5)	1.5 (0.1)	9.3 (0.2)
10	37.8 (1.2)	3.3 (0.1)	3.9 (0.3)
20	50.9 (0.9)	4.6 (0.1)	3.1 (0.1)
30	58.5 (4.3)	5.9 (0.2)	3.0 (0.2)

Tab. 1 Mechanical properties of uncoupled FG composite.

Reinforcement (wt%)	Coupled-fiberglass composites		
	σ_t^c (MPa)	E_t^c (GPa)	ε_t^c (%)
0	27.6 (0.5)	1.5 (0.1)	9.3 (0.2)

10	43.9 (0.7)	3.3 (0.1)	4.4 (0.3)
20	66.7 (0.7)	4.5 (0.2)	3.5 (0.3)
30	84.1 (0.3)	6.0 (0.1)	3.2 (0.1)

Tab. 2 Mechanical properties of coupled GF composite.

Reinforcement (wt%)	**Coupled-stone groundwood composites**		
	σ_t^c (MPa)	E_t^c (GPa)	ε_t^c (%)
0	27.6 (0.5)	1.5 (0.1)	9.3 (0.2)
10	34.2 (0.1)	2.2 (0.1)	6.9 (0.1)
20	40.6 (0.3)	3.1 (0.1)	4.85 (0.2)
30	46.8 (0.2)	3.75 (0.1)	4.35 (0.15)

Tab. 3 Mechanical properties of coupled SGW composite.

In Table 1, 2 and 3, are presented the tensile properties of polypropylene and PP composites reinforced with sized-fiberglass, coupled-fiberglass, and coupled-stone ground wood.

Table 1 shows the mechanical characteristics of fiberglass polypropylene composites. Although the obtained values were noticeable, and the improvements with respect to non-reinforced polypropylene were high, we knew from other researcher's works that the interface between fiberglass and polypropylene was improvable by adding coupling agents. Table 2 shows the obtained results when MAPP was added to the composite. In fact, mechanical properties of the material improved quickly, and the ratios of improvement when compared with the raw material were higher. The Young's modulus of the composites was not noticeably affected by the addition of MAPP.

Table 3 shows the mechanical properties of coupled SGW-PP composites. The effect of coupling agents is more noticeable in the case of natural fibers due to That result is caused by the significant difference in polarity surface charge density between the matrix and reinforcement, resulting in a bad interface [4]. Nonetheless, the improvement of the mechanical properties is lower than that achieved with FG.

Outdoors furniture is usually made of FG-PP composites and the most common percentages of FG are 10 to 20%. If that material were to be substituted by SGW-PP composites, similar mechanical properties were to be achieved. Comparing the data on tables 1 to 3 it was observed that a 30% SGW-PP composite showed similar strengths that 20% uncoupled FG-PP composites and 10% coupled FG-PP composites.

3.2 Product design

Product design is a key factor in the decision to buy a new product. Well-designed products add competitive advantages in front of analogous products with comparable quality levels. Hence, was necessary to take in account the user's needs and preferences, by knowing the functional features wanted by the potential customers, and by analysing how similar products are used. The final output was the checklist with the fundamental characteristics that a new product must incorporate.

In the design stage, and with the objective of establishing a final design solution for a new product, a list of economical, technical, market, use, human factors, and aesthetic requirements were to be taken in account. Any of the requirements was able to be an innovation. Innovations are not restricted to technological aspects; hence any design requirement was treated as a potential source of innovations.

In the present case the use of a material reinforced with natural fibers from agroforestry adds value to the design, linking the solution with an environmentally friendly component.

The market requirements were first that were established. It were defined the segment, the range and the target customers. Se customer was generic and wide, and the market segment was middle end.

All the technical parameters were defined and adapted to the available composite materials properties. Rotational moulding was chosen as the manufacture method.

First of all, a study on the ergonomics of the bench was conducted to determine a good use relationship between the user and the product. The anthropometric aspects and metrics were defined, especially that related with biomechanics, and physical, sensorial and psychological comfort. The dimensions of the bench were defined. In addition other aspects as temperature variations, the possibility of generate groups and bad use.

Once the basic dimensions were defined the aspects related with the character of the product were treated. The product was to have own character and fulfil all the listed requirements. In that sense, the shape was seen as the synthesis of a process in which multiple requirements should be organized to create a balanced structure. This equilibrium had to take into account the perspective of the potential user and the usage environment (outdoors for that product). If the relation between the product and the user is not straight then the functionality is the paramount criteria.

On the other hand, there exist products were the main criteria is the functional relation between the users and the product. That the reason because, for some kinds of products, the utilitarian requirements are as important as the technical requirements. At the same time, the shape of the product must be adapted to the cultural and social aspects of the target customers. [5]

Usually the functional aspects are treated earlier to latter work on the aesthetics (Fig. 2). Hence, the next step consisted in the definition of the product shape, taking in account all the functional requirements, understanding function as usefulness and meaning. A function is not only "practical usefulness", it is also meaning. Form and function are two qualities intimately linked to a product. Form must intuitively define the function.

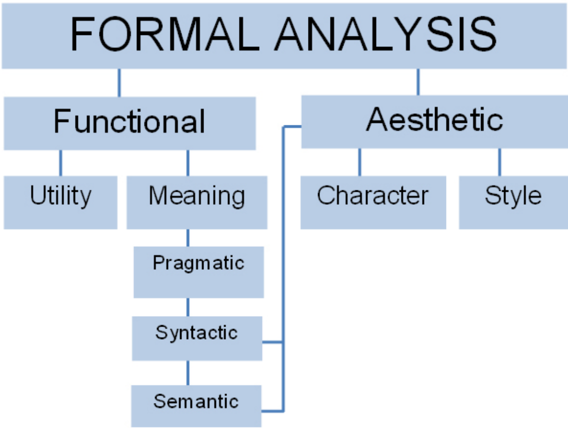

Fig. 2 Product formal analysis

In relation with the usefulness, the easiness and comfort of use were analysed. The functional analysis was valuable to establish the required bench features and create different levels, from basic features to secondary ones. The sequence of use of the product was written down, and all the sequences generated use information defining problems and opportunities. Solutions to weather changes, bad use of the product, vandalism, or maintenance were treated. Subsequently the aspects related with the intended meaning of the product were treated.

The usability and aesthetic factors were studied in accord with the investigations of Kurosu and Kashimura [6], who demonstrated the importance of usability and aesthetics for the products. That fact was validated by Tractinsky [7-9], who repeated the research. In his first work, Tractinsky denoted that in an aesthetically correctly designed product the usefulness was a very important feature. Consequently, aesthetic and use considerations must be intimately linked. Usefulness has an emotional aspect, meaning that a product that seems easier to use is better accepted by the market, has a longer lifecycle, favors the creative thinking and promotes positive relation. Renz [10] also remarked that a well-designed product has better market acceptance. Consequently, a decorative and dynamic character was defined for the bench. The ease of use for different kind of users was also established.

Therefore, the semiotic triangle proposed by [11-12] and others was used to find the conceptual solution of the bench. This interpretation leads to three dimensions – the pragmatic, the syntactic, and the semantic – to support the formal structure [13]. The pragmatic dimension is related to the practical, technical, and usage functions.

The pragmatic vision, linked to the philosophic movements leaded by C.S. Peirce and W. James at late XIX, corresponds with the practical and technical functionalities. In our case, the bench should include the basic conditions for someone to sit down and stand up with comfort. It was also sought to be an ergonomic bench chair with easy mobility, able to be placed in a private garden, terrace café, or in a lounge.

The syntactic dimension corresponds to the structural functions. In this case, the chair should support heavy weights. The proposed structure was the classical four-leg chair with arms to facilitate the sit up movement. A comfortable resting position was also desired. The syntactic dimension is also related with the structural features. Bench ought to be able to withstand large loads. Another significant point was avoiding the risk of accidents. It was also considered the possibility of designing a modular structure.

The semantic dimension gave rise to symbolic values [14]. As researched by Grande [15], the semantic value of an object is related with the object and with the environment was it is placed. In addition perception is influenced by the culture and society. We followed the postulates proposed by Kun-An and Lin-Lin [16], in which the form perception is due to four affective factors: the trend factor, the emotion factor, the complexity factor, and the power factor. These same factors were also proposed by Ai Ching and Hoon [17] by using other names such as competition, excitement, sophistication, and sincerity. In relation with the language of sings and meanings we placed as an objective that the bench had to transmit the idea of a couch without turning into one.

Next step was the aesthetic analysis, deeply related with emotional aspects which are highly relative and difficult to measure. Firs at all it was ensured the harmony of the proportions, always having in mind the ergonomics. Subsequently, and from the market analysis data, the market trends were identified and the way to incorporate them into the product character.

In reference to style and fashion, by means of the market analysis, it was observed the fashion trend to imitate indoors furniture. We introduced also the intention to apply a soft line character, very usual for that kind of furniture. Additionally we intended to adopt an organic character, to establish a conceptual relation between the product and the environment, very appropriate, taking in account the outdoors use of the bench.

The projected character of the product must respect the coherence of the product, combining some features and creating links between them, creating a final integration [18-19]. It was decided that the bench must reflect friendliness and youngness. It was also defined an approach to simplicity, with a certain grade of rhythm based on the repetition.

Fig. 3 First sketches to find project ideas

Once all the design specifications were defined the conceptualization phase started. The first ideas were sketched (fig. 3). The conceptual design is intended to be a heuristic process, and never an exact science [20]. Hence the correct approach must be based on a deductive strategy of gradual discovering. The sketches were a fast way to approach the first ideas [21].

With the objective to generate as much ideas as possible two creativity sessions were scheduled. The first sessions consisted in the use of brain drawing techniques, a mixture of brainstorming with sketches [22]. The second half of the session consisted in a morphological analysis (Zwicky box), were a list of evaluation criteria was written down and every criteria was weighted. Later on all the ideas were evaluated and classified by means of the weighted criteria. The chosen alternatives were the highly qualified ones. The second session used SCAMPER techniques to, in first instance, wide the focus of opportunities, and secondly to revise critically the chosen ideas [23].

The next step comprised the development and widening of the scope of the chosen concepts. From the initial sketches a series of alternatives were developed. The alternatives consisted in little modifications of the chosen concepts with the objective of refining the concept without changing the essence of the concepts. In a subsequent meeting the ideas that better incorporate the briefing requirements were chosen (Fig. 4).

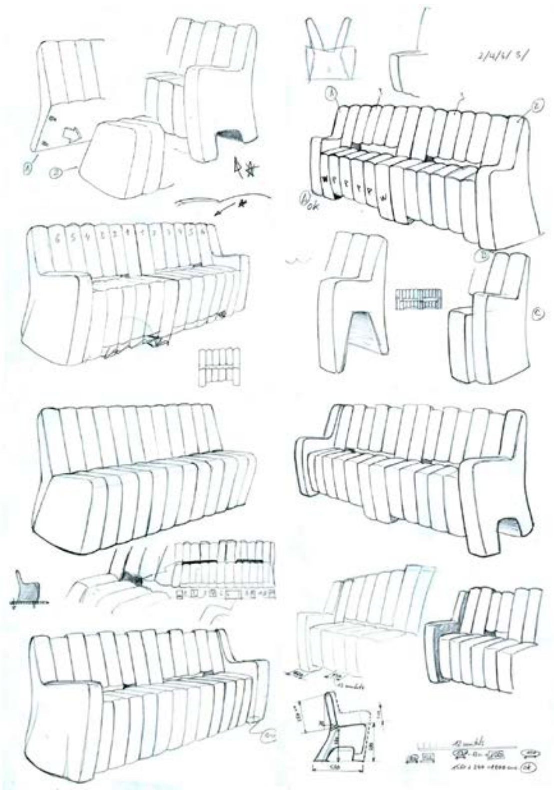

Fig. 4 Development of the selected model

Once the definitive conceptual alternative was chosen, the design process continued by means of 3D modelling (Fig. 5). The model was further developed by the product engineers, to prevent a collapse of the structure under load. At the same time different proposals regarding color and surface finish.

Fig. 5 Final developments and 3D mock up.

Finally the placement of the product was simulated by means of a series of photomontage. The green tonalities used in the final proposal, with two variants, were based on its natural environment proximity. It was very important the contrast and harmony between the colors.

Fig. 6 Photomontages of the designed bench on two possible locations.

3.3 Product engineering

The input data for product engineering were product geometry, production technology, and the use specifications. The geometry was a CAD 3D virtual model D, the production technology was rotational moulding. The use specifications were based on tree load hypothesis. H1: Adult seated properly, H2: adult seated in bench back. H3: combination of H1+H2 [24-25].

The geometric definition had to be adapted to the production technology. In this case, a thickness of 8 mm was established. It is well known that after production, the internal width of the bench will not be constant, therefore, a less favourable situation was assumed for the requirement calculation. The geometric model for the calculation did not consider rounded edges, so a stress concentration in the base of the chair legs was expected, which involved an extra security factor. The process doesn't allow rigidifying by adding ribs, so we worked the geometry.

Additionally, in order to agree with legal specifications, final products or proto-types must be submitted to a series of tests. However, a minimum number of prototypes and design modifications had to be completed in order to economize the process. The use of computer aided engineering (CAE), such as finite element analysis, allowed time to be cut from the development and the cost of the design process [26].

The digital mockup was prepared and meshed with 3D tetrahedral finite elements. The dimension of the element was refined at the union between seat and back. The loads were estimated considering a 99% percentile European male. Bench legs were restrained in their movement along the plane. One of the legs was totally immobilized and the rest were restrained to move in the floor plane. Once all the restrictions and loads were applied the calculus process was started.

The highest requirements were obtained from the results of the static load test H3 (Fig. 3). From the static load test, where the bench was submitted to 250 kg of weight onto its base, and 300 onto the back the value for tensile-compression strength was obtained, which was 25.8 MPa. When a 1.3 safety factor was applied it was obtained a target 33.54MPa tensile strength. The tree possible composite materials were PP reinforced with, 10% uncoupled fiberglass, 10% coupled fiberglass and 20% coupled SGW.

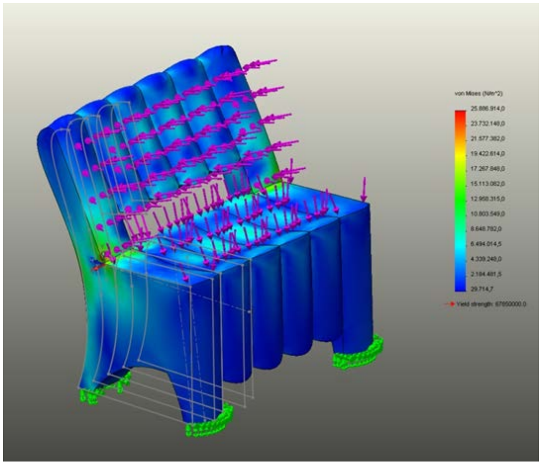

Fig. 7 With the 2.2 GPa Young's modulus the maximum strain was 9 mm at the back of the bench, a value that represents the 2% of the length of the back.

Afterwards, the product strains were studied in order to establish the minimum value for the Young's modulus. For this aim, back was analysed, as it supported the higher deformation. A maximum strain of 10% of the total height was established as acceptable, 82 mm in this case, due to flexural loads. The calculus involves cyclic sequential estimations to establish superior and inferior levels for the Young's modulus. According to Fig. 7, the strain behaviour was acceptable with Young's modulus around 2.2 GPa. Such values were showed by all the composite materials.

The analysis showed the feasibility of natural fiber composites to substitute FG composites. A 20%coupled SGW-PP composite showed mechanical properties that allowed its use instead of 10%FG-PP composites. Advantages of natural fibers in composites are high availability, biodegradability, low cost and low density.

4 Conclusion

Due to environmental awareness, interest in natural fibers as an alternative to FG as reinforcement in polymer composites has grown and generates a great deal of interest. That work showed the ability of natural fiber to substitute FG as reinforcement. Natural fiber composite material proved its capabilities as a substitutive of less environmentally friendly materials for semi structural applications. The lifecycle of the final product benefits from the use of that kind of materials.

It is possible to achieve value from the use of new composite material reinforced with natural fibers from agroforestry by mean of product design and development. The environmentally friendliness of the material adds value to the final product. The use of finite element analysis shortened the design process, avoided the production of mockups, and ensured the technical viability of the project.

The presented design and development process adds a multidisciplinary view, widening the scope of expertise to applied sciences. Usually product design and development is carried out by designers and engineers, and the scientific point of view keeps missing. The relation established between the experts to create the new product evolved to a long life relationship that enriches all the research groups, with new research lines.

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