BIO-BASED COMPOSITES FROM STONE GROUNDWOOD APPLIED TO NEW PRODUCT DEVELOPMENT

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This paper deals with the product design, engineering, and material selection intended for the manufacturing of an eco-friendly chair. The final product is expected to combine design attributes with technical and legal feasibility with the implementation of new bio-based materials. Considering the industrial design, a range of objectives and trends were determined after setting the market requirements, and the final concept was proposed and modeled. The product geometry, production technology, and legal specifications were the input data for product engineering. The material selection was based on the technical requirements. Polypropylene (PP) composite materials based on coupled-fiberglass, sized-fiberglass, and coupled-stone ground wood reinforcements were prepared and characterized. Final formulations based on these PP composites are proposed and justified.

Keywords: Discontinuous reinforcement; Polymer-matrix composites (PMC); Finite element analysis (FEA); Natural fiber; Mechanical properties.

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INTRODUCTION

Currently, new product development (NPD) is the term used to describe the complete process of bringing a new product or service to the market. There are two parallel paths involved in the NPD process, the idea generation, product design, and engineering on the one side, and the market research and marketing analysis on the other side. This type of development is considered the preliminary step in product or service development, and it involves a number of steps that must be completed before the product can be introduced to the market. New product development is essential to any business that must keep up with market trends and changes.

In business and engineering, new product development is a multidisciplinary process in which many different experts have to communicate efficiently. All the personnel involved must share a common language to guarantee accurate transmission of the information concerning industrial design, product engineering, and material science in order to ensure the quality of the final product. Existing research has consistently recognized the quality of collaboration within teams as an important factor to successful innovations (Sethi 2000). Consequently, product designers should realize social needs and convert them into product concepts by using functional, aesthetic, and emotional features (van Kleef *et al.* 2005). Product design is very often the key feature in determining the product acquisition. Well-designed objects show competitive advantages over others with similar quality and performance (Bloch 1995). Nowadays, the functionality is not the only criterion determining the shape of an object.

The product design process is a set of design activities. There are various interrelations among these activities. Coupled relationship means that the decision of one activity will affect one or more other activities, and vice versa. The interdependency degree between them is very high, and there are information exchanges among the coupled activities. Such interdependency needs many iteration loops to set all design information in a consistent way, and the coupled activities need to be performed concurrently (Tang *et al.* 2000). Product engineers have to warrant the viability of the final product and perform any modification to the geometry in order to assure the product manufacturing and the technical requests of the final product. The result of this stage is a virtual model and the determination of specifications for the final product. Finally, the experts on material science should be able to fit the technical requirements with a suitable material. In the end, the specialists, working together, will comprehend the viability of the final product from the technical, economical, and market points of view.

It is possible to understand new product development as a three-step process in which the outputs of one step are used as the inputs of the following, as shown in Fig. 1. In this context, the final product combines attributes of added value, thanks to the design, with technical and legal feasibility, thanks to product engineering. This may involve new materials – an approach that offers uniqueness to the final product in comparison with its counterparts.

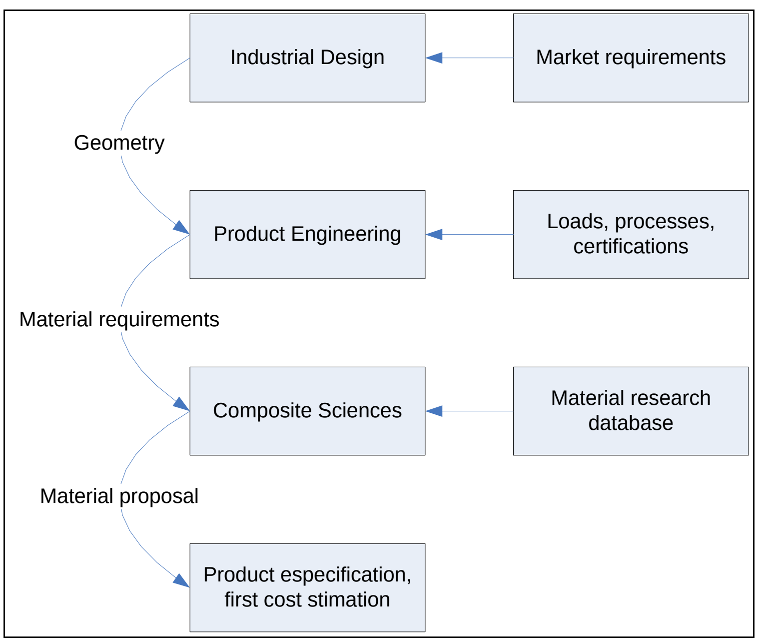


Fig. 1. Research framework for new product development

In terms of materials selection, the current tendency is to look for natural-based composites to take into account the sustainability of the final product. Natural fiber composites are environmentally superior to glass fiber composites due to the lower environmental impact when produced, the higher fiber content of the natural fiber composites which reduces the amount of base polymers, and the possibility of incinerating the polymers at the end of product life (Joshi *et al.* 2004; Zini and Scandola

2011). Natural fibers or cellulosic fillers/fibers can be classified into four categories depending on their performance when incorporated in a polymeric matrix: i) wood flour or agroforestry waste flour in general, ii) wood fibers iii) natural strands or bundles of strands, and iv) fibers from agroforestry residues. Wood flour and other low-cost agricultural based flour can be considered as particulate fillers that enhance the tensile and flexural moduli of the composites with little effect on the composite maximum sustainable load (Rowell *et al.* 1997; Flandez *et al.* 2012). Wood fibers (Lopez *et al.* 2011), such as mechanical pulp, have higher aspect ratios and contribute to an increase in the moduli of the composite; they can also improve the strength of the composite when suitable additives are used to improve the stress transfer between the matrix and the fibers (Lopez *et al.* 2011; Mutje *et al.* 2007; Vilaseca *et al.* 2010).

Although several plastics have been used as a matrix of cellulosic fibers, the major part of the work has been on polypropylene (Beckermann and Pickering 2009; Bourmaud and Baley 2007; Coutinho *et al.* 1997; Franco-Marques *et al.* 2011; Niu *et al.* 2011). The work reported here will concentrate on this versatile plastic in combination with stone ground wood fibers. In this work, researchers from design and product innovation have worked together with experts in materials science in the development of an eco-chair. The new product development combines innovative targets in design and product conception, as well as the application of new materials in order to fulfill the final requirements of the market subsector. Usually such products are produced with fiberglass reinforced composites. The properties of polypropylene composites reinforced with fiberglass are compared to those that were reinforced with stone ground wood, and its suitability are analyzed in the view of the production of the product.

MATERIALS AND METHODS

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-molding 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.

Industrial Design and Product Engineering

Industrial design

The product was designed using traditional monochrome techniques. Starting with some initial ideas, the concept was refined.

Product development

The three-dimensional prototype and the analysis of the chair were developed with the CAD/CAE platform, SOLIDWORKS, by Dassault Systemes.

Composite Materials Development and Characterization

Fiber individualization

Stone ground wood (SGW) was disintegrated in a pulper device (Pulcel, Tolosa, Spain) to induce fiber individualization. A suspension of the SGW in diethylene glycol dimethyl ether (diglyme) and water (2/1 v/v; 5 wt % consistency) was placed in the pulper for 1100 revolutions. Once the SGW was disintegrated, the resulting fibers were dried at 80 ºC until a constant weight was obtained.

Composite preparation

PP, SGW, and MAH–PP were dried before their use in an oven (at 80 ºC without a vacuum for 48 h). 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 80 ºC for 24 hours.

Injection molding

Pellets were injection-molded into a Meteor-40 injection molding machine (Mateu & Solé, Barcelona, Spain) to obtain tensile, flexural, and impact specimens. The injection molding temperatures were in the range of 168 to 186 ºC. The first and second pressures were 120 and 37.5 kgf/cm^2.

Mechanical characterization

Composite specimens were conditioned at 23 ºC and 50% humidity for 24 hours before testing (ISO D618). The tensile and flexural tests were carried out with an Instron 1122 universal testing machine (Zamudio, Spain) according to ASTM D 638 and ASTM D 790 standard specifications, respectively. The impact test was performed with a Charpy pendulum according to ISO 178, providing the impact strength.

RESULTS AND DISCUSSION

Industrial Design

In industrial design, the final solution of the product concept is usually constrained by different requirements under the economic, technical, market, functionality, usage, ergonomic, and aesthetic considerations.

In this study, after setting the market requirements of an eco-chair, a range of objectives and trends were determined. The objectives, market trends, and specifications were based on a prior chair design project made by the product design department.

First of all, practical parameters such as functionality, usage, and ergonomics, together with limiting technical requirements, were defined, and the basis of the general shape and details were established. 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 (Toomingas and Gavhed 2008). For this reason, the ergonomics and semantic considerations show, very often, a similar significance compared to the technical aspects (Howard *et al.* 2010). The considered dimensions for the design were: a width of about 450 mm, a depth of 500 mm, and a medium height of 460 mm for the chair, 650 for the armrest, and a maximum height of 840 mm.

Therefore, the semiotic triangle proposed by Krampen and Hauser (1986), Mukarovsky (1978), and others was used to find the conceptual solution of an eco-chair. This interpretation leads to three dimensions – the pragmatic, the syntactic, and the semantic – to support the formal structure (Capela *et al.* 2010). The pragmatic dimension is related to the practical, technical, and usage functions. In our case, the chair should include the basic conditions for someone to sit down and stand up with comfort. It was also sought to be an ergonomic 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 semantic dimension gave rise to symbolic values (Chang *et al.* 2006). We followed the postulates proposed by Hsiao and Chen (2006), 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 Lim and Ang (2008) by using other names such as competition, excitement, sophistication, and sincerity.

Within the language of symbols and meanings, we wanted the chair to perceptually transfer the idea of an armchair without turning into one. In relation to the style, we decided to join two different genres: the neo-baroque style, now widely used in furniture, and the organic style, to capture the essence of nature.

The emotional relationship between the user and the product is determined, to a large extent, by the symbolic dimension of the product (McDonagh *et al.* 2002). The eco-chair should have an attribute directly related to emotions, which corresponds to its personality. The goal was to achieve integration of the combined characteristics, and to merge them into a coherent whole (Mugge *et al.* 2009). The eco-chair should have a friendly and elegant character. For this last aspect there was an appeal to musical connotations. Regarding the simple-complex factor, a straightforward appearance was evoked, with a somewhat sophisticated class. Finally, it was decided to introduce the perception of lightness and delicacy, which is related to elements existing in nature such as clover leaves.

After the definition of objectives, the ideas were conceptualized in sketches. This stage is, of course, not an exact method, as it shows heuristic character. It is a working approach using a deductive strategy of gradual breakthrough. During the procedure, some creativity techniques were used. The alternatives consisted of brief adjustments (*i.e.* “briefing”), while protecting the spirit of the initial concepts. In the last step, a final design was selected that more accurately fit the requirements proposed in the briefing.

The final conceptual alternative was then modeled in a 3D digital model (Fig. 2), and the final eco-chair dimensions were proposed.

Product Engineering

The input data for product engineering were product geometry, production technology, and the legal specifications. The geometry was a CAD 3D virtual model D, the production technology was gas-assisted injection molding, and ANSI/NIFMA X.5.1-2002 and BS ENV 581-2:2000 were the standard specifications to follow.

Fig. 2. Conceptual design of the eco-chair

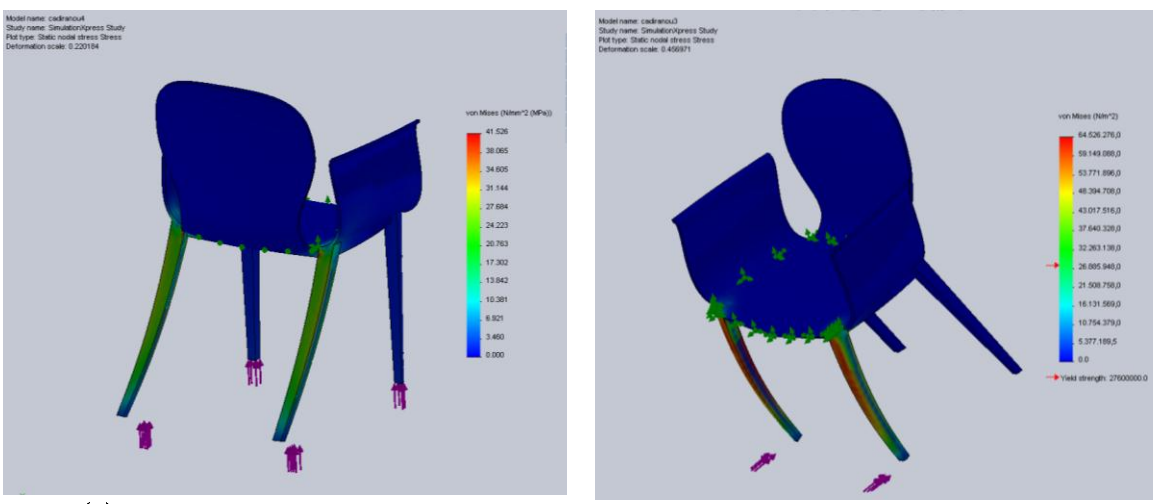
Table 1. Outline Conditions and Verification Tests

Test name	Standard	Loads and constraints	Expected output
Horizontal arm load test	ANSI/BIFMA X.5.1 – 2002	40 kg load placed on middle arm frame. Test duration: 1 minute.	No permanent deformation with 40 kg load.
Vertical arm load test	ANSI/BIFMA X.5.1 – 2002	Chair prevented from moving by stops. 150 kg load on front arm frame. Test duration: 1 minute.	No permanent deformation with 150 kg load.
Static load test (Base durability)	Adopted from MTL Test Laboratories	250 kg load placed on seat. Test duration: 1 minute.	No structural failure after static load test
Leg load test	ANSI/BIFMA X.5. 1	Chair placed horizontally & prevented from moving by stops. 40 kg load suspended from 4 legs in 4 directions. Test duration: 1 minute / leg.	No structural failure when 40 kg lateral force applied to leg at 1 inch from end of leg. Force applied in 4 directions for 1 minute (fore, rear, left, right).
Push test	BS 4875 : Part 5 : 2001 (BS EN 1730,6 .4)	Chair prevented from moving by stops. 50 kg load on seat center. Push right & left arm frame in turn. Tests: 15,000 /arm.	Deflection of greater than 4 mm not acceptable during test.

The geometric definition had to be adapted to the production technology. In this case, a thickness of 8 mm and the gas injection on the legs was established. It is well known that after production, the internal width of the chair legs will not be constant (Chen *et al.* 2011), therefore, a less favorable 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. Some ribs between the chair legs were molded to ensure the mechanical stability as well to provide a channel for the gas injection.

Additionally, in order to agree with legal specifications, final products or prototypes 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 (Fujii *et al.* 2001). For the present case, the following tests were established (Table 1).

The highest requirements were obtained from the results of the static load test (Fig. 3a) and the vertical arm load test (Fig. 3b). From the static load test, where the chair was submitted to 250 kg of weight onto its base, the value for tensile-compression strength was obtained, which was 42 MPa. In the vertical arm load test, the chair legs were submitted to a perpendicular load of 150 kg of weight, and a flexural momentum over the chair base was created so that a value of flexural strength of 65 MPa for the final product was obtained.



(a) (b)

Fig. 3. Results from the analysis of the static load test (a) and the vertical arm load test (b) for static nodal stress

Afterwards, the product strains were studied in order to establish the minimum value for the Young's modulus. For this aim, the back legs were analyzed, as these were the ones supporting 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. 4, the strain behavior was acceptable for Young's modulus up to 3.5 GPa.

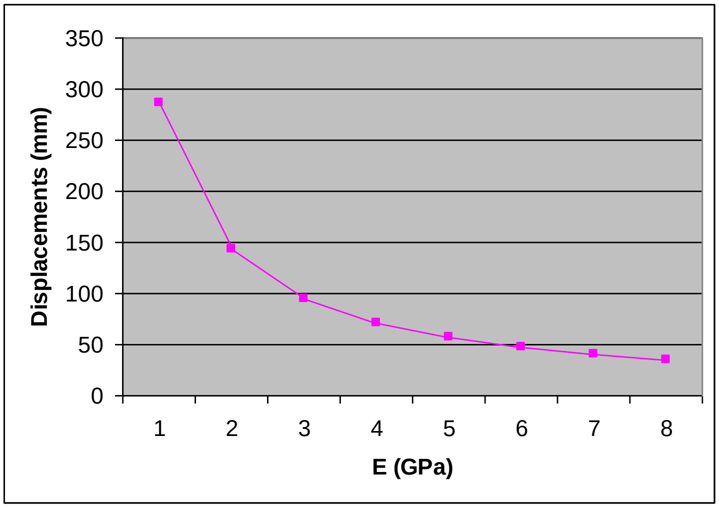


Fig. 4. Obtained displacements in the model function to the Young's' modulus

Composite Material Selection

The common materials that are used for the production of these types of products are fiberglass/PP reinforced composites. Both polypropylene and fiberglass 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) (Lopez *et al.*, 2011). 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 analyzed in the view of the production of an eco-chair.

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

Table 2. Tensile Properties of Polypropylene and PP Composites Reinforced with Sized-Fiberglass, Coupled-Fiberglass, and Coupled-Stone Ground Wood (SGW). Standard deviation in brackets

Reinforcement (wt%)	**Sized-fiberglass composites**			**Coupled-fiberglass composites**			**Coupled-stone ground wood composites**		
	σ_t^c (MPa)	E_t^c (GPa)	ε_t^c (%)	σ_t^c (MPa)	E_t^c (GPa)	ε_t^c (%)	σ_t^c (MPa)	E_t^c (GPa)	ε_t^c (%)
0	27.6 (0.5)	1.5 (0.1)	9.3 (0.2)	27.6 (0.5)	1.5 (0.1)	9.3 (0.2)	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)	43.9 (0.7)	3.3 (0.1)	4.4 (0.3)	34.2 (0.1)	2.2 (0.1)	6.9 (0.1)
20	50.9 (0.9)	4.6 (0.1)	3.1 (0.1)	66.7 (0.7)	4.5 (0.2)	3.5 (0.3)	40.6 (0.3)	3.1 (0.1)	4.85 (0.2)
30	58.5 (4.3)	5.9 (0.2)	3.0 (0.2)	84.1 (0.3)	6.0 (0.1)	3.2 (0.1)	46.8 (0.2)	3.75 (0.1)	4.35 (0.15)

A linear evolution of the tensile strength and the Young's modulus with the fiber content in each composite was observed. In the case of fiberglass composites, the influence of the quality at the fiber-matrix interface has been pointed out. The compatibility factor (f_c), derived from the rule of mixtures (Fu and Lauke 1996) (Eq. 1), was found to be 0.117, 0.178, and 0.207, respectively for sized-fiberglass/PP composites, coupled-fiberglass/PP composites, and coupled-SGW/PP composites, comprising 20 wt% of reinforcement. For this calculation, the volume fraction of the composite was required, as well as the intrinsic tensile strength of the reinforcing fiber, which was 2415 MPa for sized-fiberglass, 2955 MPa for coupled-fiberglass, and 600 MPa for coupled-stone ground wood fiber.

$$\sigma_t^c = f_c \sigma_t^F V^F + (1 - V^F)\sigma_t^{m,*} \quad (1)$$

In Equation 1, σ_t^c and $\sigma_t{}^f$ refer to the tensile strength of the composite and the fiber respectively; $\sigma_t^{m,*}$ is the tensile strength of the matrix at composite failure, f_c is the compatibility factor at fiber matrix interface, and V^F is the volume fraction of the reinforcement. The compatibility factor deals with the stress transfer quality at the fiber-matrix interface. In the literature, it is found that the compatibility factor is around 0.2 for well-bonded composites (Sanadi *et al.* 1994). In the present case, coupled-fiberglass composites exhibited better stress-transfer than sized-fiberglass composites. Coupled-SGW composites showed a better response at the interface.

The composite material was selected based on Fig. 5. According to the product engineering, the tensile strength of the desired product should be 42 MPa and the stiffness should be 3 GPa. From the analytical equation, it is deduced that the technical demand would be accomplished by composites comprised of 7.5 wt% of coupled-fiberglass composites, 13.5 wt% of sized-fiberglass composites, and 22.35 wt% of coupled-SGW composites. In these conditions, the stiffness of the ensuing composites has to be considered.

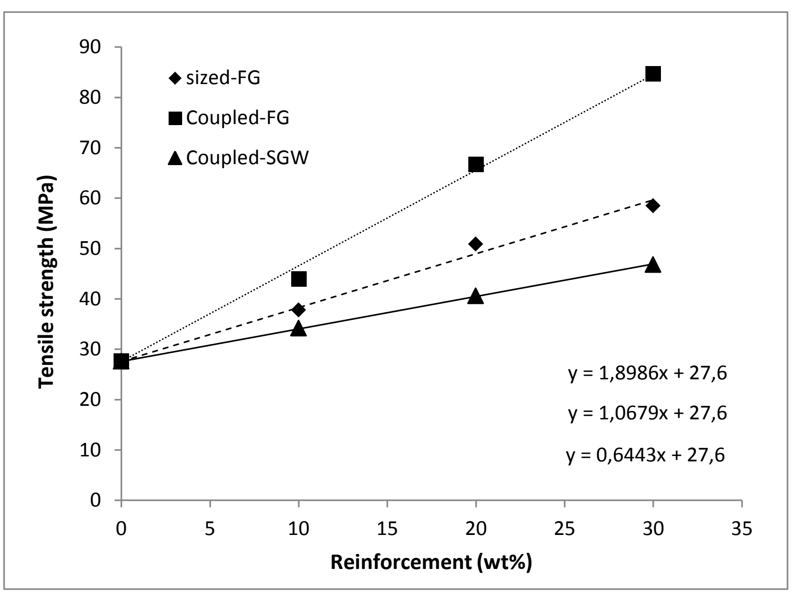


Fig. 5. Tensile strength of the studied composites with the weight percentage of the reinforcement

The analytical relationship between Young's modulus and the fiber content in weight is E_t = 0.1514*wt%+1.5 for fiberglass composites and E_t = 0.0761*wt% +1.5 for SGW composites. Afterwards, the stiffness of the ensuing coupled-fiberglass composite (comprising 7.5 wt%) would be 2.6 GPa, the stiffness of sized-fibreglass composite (13.5 wt%) 3.5 GPa, and the rigidity of SGW composite (22.35 wt%) would be 3.2 GPa. In terms of tensile demand, composites comprising 13.5 wt% sized-fiberglass or comprising 22.5 wt% of SGW would fit with the technical requirements for the manufacturing of the designed product. In order to use coupled-fiberglass composites, the minimum weight percentage should be 10 wt%.

The flexural and impact properties of the composites are shown in Table 3.

Table 3. Flexural and Impact Properties of Polypropylene and PP Composites Reinforced with Sized-Fiberglass, Coupled-Fiberglass, and Coupled-Stone Ground Wood (SGW) (standard deviation in brackets)

Reinforcement (wt%)	**Sized-fiberglass composites**			**Coupled-fiberglass composites**			**Coupled-stone ground wood composites**		
	σ_f^c (MPa)	E_f^c (GPa)	I^c (kJ·m^{-2})	σ_f^c (MPa)	E_f^c (GPa)	I^c (kJ·m^{-2})	σ_f^c (MPa)	E_f^c (GPa)	I^c (kJ·m^{-2})
0	40.2 (0.5)	1.1 (0.1)	---	40.2 (0.5)	1.1 (0.1)	---	40.2 (0.5)	1.1 (0.1)	---
10	63.1 (1.2)	2.3 (0.1)	23.1 (1.2)	68.3 (1.1)	2.4 (0.1)	26.8 (1.3)	50.9 (0.9)	1.5 (0.1)	27.5 (1.1)
20	78.0 (0.9)	3.2 (0.1)	18.9 (1.0)	94.8 (2.0)	3.2 (0.2)	22.7 (1.3)	57.4 (0.9)	2.1 (0.1)	23.5 (1.2)
30	88.1 (2.0)	4.7 (0.2)	17.7 (0.9)	109.8 (2.0)	4.7 (0.1)	21.4 (1.0)	70.2 (1.1)	2.8 (0.1)	20.7 (1.1)

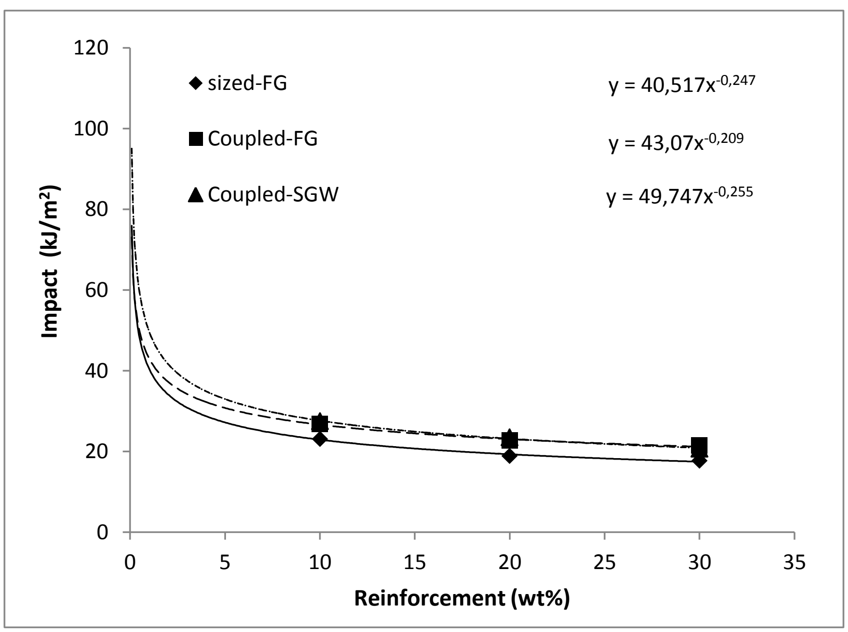


Fig. 6. Impact strength of the studied composites with the weight percentage of the reinforcement

The technical requirement for the designed eco-chair entailed a flexural strength of 65 MPa. The application of the theoretical percentages of the reinforcement to the analytical equation of flexural strength does not accomplish the desired value for flexural strength, as it was 61.6 MPa for coupled-fiberglass composites (7.5 wt%), 64.8 MPa for sized-fiberglass composites 13.5 wt%), and 61.75 MPa for coupled-SGW (22.35 wt%). A slight increase on the fiber content was needed for each composite. Therefore, the target percentage is 10 wt% for coupled-fiberglass/PP composites, 15wt% for sized-fiberglass/ PP composites, and 25 wt% for coupled-SGW/PP composites.

Finally, the evolution of the impact strength for coupled-fiberglass composites was similar to that of coupled-SWG composites (Fig. 6). For the composites comprising the reinforcement percentages chosen for manufacturing, the absorbed energy for a break to occur would be 26.6, 21.0, and 22.1 kJ/m^2, respectively, for coupled-fiberglass, sized-fiberglass, and coupled-SWG composites. The commercial requirements of the design were 22 kJ/m^2; therefore composites comprising 25 wt% of SWG of reinforcement would fit the technical requests.

It is stated that the manufacturing of the eco-chair can be carried by using PP composites comprising 10 wt% of coupled-fiberglass, 15 wt% of sized-fiberglass, or 25 wt% for coupled-SGW reinforcement. From an economic point of view, a rough approximation for the cost of the materials, referred from prices of 2012, can be given considering the raw materials cost for each formulation: polypropylene 1.1 €/kg, fiberglass 1.3 €/kg, coupling agent 2.5 €/kg, and 0.35 €/kg for stone ground wood. An amount of 0.24 €/kg was considered as the production cost in each case. Therefore, values of 1.39 €/kg for composites at 10 wt% of coupled-fiberglass, 1.37 €/kg for composites at 15 wt% of sized-fiberglass, and 1.19 39 €/kg for composites with 25 wt% for coupled-SGW reinforcement were obtained. One can say that both fiberglass composites (10 wt% of coupled-fiberglass or 15 wt% of sized-fiberglass) would cost around 1.4 €/kg, while the rate would be around 1.2 €/kg for the stone ground wood composite (25 wt%). This consideration suggests that the use of SGW/PP composite for the manufacturing of the designed eco-chair would result in a saving of plastic material and provide a more sustainable and recyclable final product, while still achieving the economic and technical objectives.

CONCLUSIONS

1. Idea generation, product design, and engineering can be combined as a path towards new product development, which is a preliminary step in development of a product or service. Consequently, new product development is a multi-disciplinary process in which a group of specialists, functioning as a team, will comprehend the viability of the final product from points of view ranging from technical to the economical.
2. An example of sequential development from conception to material selection is given in this paper. In this case, polypropylene composites based on fiberglass or stone ground wood were compared in the manufacturing of an eco-chair. A working approach using a deductive strategy of gradual breakthrough was applied for the product design, and a final conceptual alternative was proposed. Subse-quent product engineering determined the final dimensions and technical require-

ments of the designed product. Finally, the material selection showed the viability of three different formulas for coupled-fiberglass composites, sized-fiberglass composites, and stone ground wood composites.

3. It is concluded that the formulation comprising of 25 wt% of stone ground wood accomplishes the technical requests of the designed eco-chair. This approach also was found to be the most feasible from the standpoints of economics and sustainability.

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