Characterization of beech wood pulp towards sustainable rapid prototyping

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Abstract: Wood has several advantages that are transferable to various derivates allowing the introduction of a sustainable material into the product lifecycle. Our study is to apply a DFM approach based on wood flour rapid prototyping, while associating the requirements of the "mass market product" in the implementation of a customized product. New communication tools allow consumers to be involved in the design process. Prototyping processes allow direct manufacturing of products.

Key words: CAD, Mass market product, DFM, DOE, modified starch, rapid prototyping, wood flour.

1- Introduction

The market for "mass market product" has evolved in recent years towards customizable products. This market change has created new offerings not based on existing markets as in the past, but generating a new application. This new behaviour has somewhat changed the decision to make process related to product design. Make a good product is necessary to be competitive, but unfortunately not enough; one should also make so the right product, that means the product that fits to the users real needs and expectations **[SG1]**. Many domains (automotive domain) use methods focused on the user. It is shown that the involvement of users and their perceptions is critical to the design **[P1, M1 and R1]**. As the manufacturability of the product is also crucial, several intrinsic parameters, related to the manufacturing process, are added to the design process. The notion of "sustainable" products is an important concept. It leads to the use of materials and manufacturing processes compatible with respect of the environment throughout the lifetime of the product. The environment of a product has an impact on its life cycle. By specifying environmental compared audits, also called life cycle analysis (LCA), we show that the wood has obvious advantages and appears as an "environmentally responsible" solution **[TT1]**.

The business purpose of the company Arduinnova, is to provide customized on demand product for the "general public" with a production of unit objects. As the reproducibility of products needs specific tools, Arduinnova has chosen the prototyping process.

This article discusses the integration of natural materials in our experimentation on beech wood pulp through two processes of prototyping for manufacturing reconstituted wood products: 3D printing and Solid Freeform Fabrication (SFF).

2- Natural materials used

2.1 – Wood flour

Wood is a biodegradable organic material which is more or less long term reinstated in the natural carbon cycle. The cycle analysis (LCA : Life Cycle Analysis or Assessment) reveals the global strengths of the material. LCA takes into account the environmental impact of the subsequent stages of the life of the wood preparation and extraction, processing, transportation, installation, performance usage and recycling. Information on the life cycle of wood are still new and dispersed **[TT1]**, but we can mention a few main areas:

-Operation is less polluting than the extraction of other materials.
-The transport does not involve any risk and its supply is closer.
-It requires less energy and less water than other materials.
-The exploitation of under-products of wood is in development, and wood energy is neutral in CO2 production.

Wood takes part in the reduction of carbon dioxide emissions as an alternative to non-renewable materials, the latter leading to energy costs and negative impacts that are hard to be sustained by our ecosystem. The life cycle of wood includes certain compounds that involve all materials using wood material processed as main base, such as plywood, particle board, fiber, etc. The interest of these products is based on their economic, technical and commercial assets. The structural differences that can be found in one essence, lead to a certain amount of qualities and criteria for variable use. Any material that has little value which can be recycled is collected, crushed, shredded, fiberised, and may result in reconditioned wood material like the wood flour, with or without the addition of binder to give advantageously paper, cardboard, fiberboard or particles **[P2]**. The timber has a very competitive sale price compared to solid wood although the mechanical performances are lower. Their techno-economic value offers significant opportunities for industry sectors of construction, layout, and furniture incorporating recognized decorative techniques. The appearance and aesthetics of wood is undoubtedly an advantage for this material. But its use in wood derivatives shows that other applications are possible without translating the aesthetic and structural advantages of wood.

With the integration of flour as main element in a process such as prototyping, it would be possible to obtain a homogeneous and isotropic material, unlike solid wood. Its high sensitivity to humidity forced to limit the use of such material. In our experiments, we use beech flour with two different grain sizes detailed in Table 1: LIGNOCEL HB 120 and ARBOCEL HW 630.

Name	*Structure*	*Grain size*	*Density*
HB 120	Fibrous	40 - 120 µm	140-200 g/L
HW 630	Fibrous	20 - 40 µm	200-300 g/L

Table 1: Beech flours.

2.2 – Modified starch

Processes operate at a temperature below 40°C for the 3D printer, and at room temperature for the deposition modelling process. We focused on native starches and modified starches to study their behaviour through research in the scientific community. Starch is the main carbohydrate reserve substance of higher plants. It represents a significant mass fraction in a large number of agricultural commodities such as cereals (30% to 70%), tubers (60% to 90%) and vegetables (25% to 50%). The native starches, as maize or wheat starch, and potato starch form a presence of water in the vicinity of 50 to 70 ° C depending on the selected starch, with a rapid recrystallization of polymers (amylose and amylopectin) to cooling, called starch retrogradation **[B1]**. There are various modified starches that improve their behaviour. The chemically modified starches develop their viscosity and their binding property at low temperature or at normal cooking temperatures in environments where water availability is limited. This category gathers those modified starches obtained by reaction of hydroxyl groups of starch with monofunctional agents to introduce substitution groups. The purpose of this type of treatment is to stabilize the amylose against the retrogradation and prevent intermolecular association of amylopectin fractions. The introduction of ester or ether groups in the starch molecule can stabilize the viscosity, especially at low temperatures **[CJ1]**. The surplus products of the reaction must then be removed by washing to obtain a completely biodegradable starch. Note that starch is sensitive to humidity and its mechanical properties decrease with increasing moisture.

For example, potato starch is used in industry to manufacture glue wallpaper, biodegradable by etherification (described in Table 2). The introduction of new hydroxylated functions provides a moisture level equivalent or superior to that of native starch. The chemicals are not longer present in the final modified product, it is completely biodegradable. However, it should be noted that the character of the starch as a natural substance decreases with increasing etherification.

Name	*Chemistry*	*Food manufacture*
Ether starch	Hydroxypropyl starch	E 1440

Table 2: Modified starch.

3- Rapid prototyping analyses

We realized the Life Cycle Analysis. It shows this process don't consumes resources but this is not the aim of the paper.

3.1 – Selection of the manufacturing process

3.1.1 –3D Printing

We had access to a 3D printer, the ZCorp 510, which by default uses a powder made from gypsum and a binder distributed by ZCorporation. Details of the compounds used are usually secret which will not facilitate the interpretation.

That technique is a mixture of projection of binder and sintering. A print head including several nozzles, to enable colour printing, throws droplets of binder over a tray of powdered material. Binder penetrates the agglomerates and the powder becomes rigid. A post-processing based glue is necessary to obtain sufficient mechanical strength.

Our choice is based on its handling, which allows us easy access to trays containing gunpowder and printing system consisting in containers, canals and printheads standard type Hewlett Packard. The entirety seemed workable for us to integrate our natural products.

3.1.2 –Deposition modelling

Solid freeform fabrication (SFF) has the potential to revolutionize manufacturing, even to allow individuals to invent, customize, and manufacture profitable goods in their own homes. The open-source Fab@Home project has been created to promote SFF technology by placing it in the hands of hobbyists, inventors, and artists in a form which is simple, cheap, and without restrictions on experimentation **[ML1]**.

The method is based on the extrusion of material in the form of paste (silicone, chocolate, pastry dough ...). One or more needles, guided by three digital axis, lay down a dough thread. The filament does not solidify immediately. The strata of the object are constructed by stacking a specific track connected with a free open-source (we can find the same type of software on the RepRap **[B2]**). The syringe connected to a plunger deposits its thread in a horizontal plane, then the platform is lowered to start make room for the next cycle. This approach could allow us to make a wood pulp to form some objects.

3.2 –Application to sustainable products

3.2.1 – Introduction

Main objective of shaping is to get aesthetical parts and to obtain mechanical properties corresponding to the constraints of use. This implies mechanical performances through tests, and good shape thanks to behaviour of the pulp (keeps its structure from the beginning to the end).

3.2.2 – From 3D Printing

On the use of ZCorp 510, we could easily incorporate the flour Beech HB 120 in the printer and do initial testing with the binding machine ZB58 transparent. The binding machine is suitable for a hydraulic material; we could assume the hypothesis that the binding machine is not as effective on wood flour. We ended up with very friable pieces in printer output. As the available sensors were not precise enough, we performed tests of toughness by penetration thanks to a low mass ball to characterize this fragility described in Table 3.

Diameter footprint	***Weight ball***	**Yield strength *Re***
4,5 mm	20 g	**1,23 MPa**

Table 3: Toughness penetration.

This result is achieved through the average of the measures of several prints on a specimen (Figure 1) placed horizontally on an undeformable support (marble of a coordinate measuring machine). The structure and brittleness give varying impressions, which bring into question the reliability of the results but allows us to devalue the fragility of the object in printer output.

Figure 1: Several prints test.

A post-treatment was considered by dipping a form in vegetable wax to increase our required forms. Tensile tests were performed on a tensile testing machine from a family of three specimens. The results of standard test-tube tension were unsatisfactory (Table4).

Captor	100 daN
Shift	10 mm/mn
Tensile	0,1 N
Ultimate strength	**1,51 MPa**
Breaking strength	0,02 MPa
Yield strength	**728 MPa**

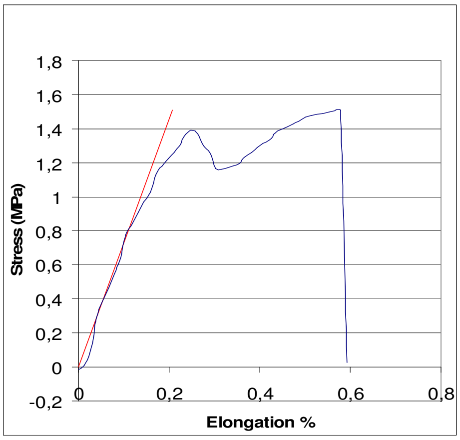

Table 4: Tensile test on a specimen soaked in a vegetable wax.

Our results are too low; we focused on the adaptation of a natural binder to project through the print heads. We encountered a lock technology, the size of the projection (in pico-liter) induced a fluid binder and a viscosity adapted to the use of print heads micro-nozzles. As our specialty is not the chemical composition of the binders, we seek suitable solutions.

3.2.3 – From deposition modelling

Because we don't have the fab @ home system, we decided to kit the manufacturing process. We are therefore using open-source software for the RepRap (RepRap for "replication rapid ") generated from a plot of the STL deposit thread paste. Then we translated specific code in gcode applicable to a CNC machine. By adapting a syringe instead of the machining system (the milling), we could confirm our application but manually making the filing of the wire, that is to say by applying manual pressure on the syringe to lodge a "wood pulp" test initially.

This first test confirm our guidance taking into account the automation of the wire deposit to be applied on the syringe, a step that does not seem to be a lock technique because we can integrate a jack or an endless screw coupling system of feeding the milling machine. The adjustment of extrusion parameters generated by the RepRap software and machining parameters to predict a step necessary for the extrusion of our pulp is workable.

We can use this manufacturing method to try to realise our wood products. The first problematic relies upon the dough consistency and notably its rheological characteristics to obtain a thread that will not collapse during the lay down. The second problematic is to respond to geometric and use constraints of the product after dough drying.

We propose to implement a design of experiments (DOE) focused on holding the wire to get the best possible deposit in the manufacture and on its geometrical and mechanical characteristics after drying.

4- Design Of Experiments for process and product characteristics identification

4.1 – Principle

The method of DOE can both reduce the number of tests, and study a large number of factors, but also to detect possible interactions between factors. The study of the influence of one factor at a given level is done by comparing the average responses obtained at this level to the overall average **[AA1 and P3]**. According to the definition of full factorial, one has an answer for each combination.

4.2 – Application

We choose to apply this method in order to discover the effects of the process and of the chosen material (thanks to the first experiences plan) on various predefined geometrical shapes without increasing tests.

Our literature search has identified influential factors such as high sensitivity of the materials to moisture (wood and starch).

Objective: *To assess the various factors that makes up pulp from its mechanical behaviour and rheological criteria.*

Consequently, the studies on the relative influence of parameters are the parameters that influence a priori significant, namely:

- The grain sizes of beech flour: 40 µm and 120 µm
- The mass of beech flour: 20 g and 40 g
- The mass of ether starch: 10 g and 40 g
- The volume of demineralised water: 200 ml and 300 ml

4.3 – Parts of tests

Test pieces are samples with non-constant geometry (Figure 2). The geometry of this is presented in picture 3 (Depending on the composition of the pulp, pieces do not look the same). The structure can vary from one specimen to another. We realize 3 samples per dough type and we will average the set of results (to avoid the spread).

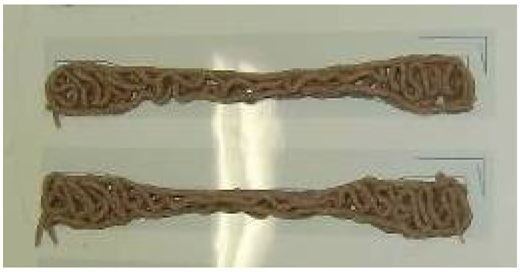

Figure 2: samples geometry

4.4 – Manufacturing conditions

We produced the test manually without CNC. Technically the filing of the wire is feasible, but our resources do not permit us to automate the descent of the plunger. Manufacturing parameters of specimens:

- Wire diameter: 2 mm
- Temperature: 20 ° C
- **Humidity: 55% RH**
- Material: Beech flour 20 µm and 120 µm (deciduous)

4.5 –Measures conditions of the mechanical

The measurement of mechanical strain is performed on a machine for strain-compression with a sensor 100 daN. The deformation is measured on the initial length (L0%); the measure of stress is MPa. The tests are conducted in an environment at a temperature and humidity of **42% RH**.

4.6 – Rheological criteria conditions

We have no tools at our disposal to directly measure the rheology of the pulp. We applied the criteria of observations to assess the wire held: Good behaviour: criterion n° 1; Medium behaviour: criterion n° 2; Worse behaviour: criterion n° 3.

4.7 – Practical method

The DOE is performed on a tension and compression machine using the conditions mentioned in the previous paragraph. We have a two-level plan, with the study of all the possible bilateral interactions per sample type, which corresponds to an L 16 table. The levels chosen are shown in table 5. The conditions were chosen on both sides of the test conditions of reference presented in the preceding paragraph.

Factors	**Level 1**	**Level 2**
Ether starch	10 g	40 g
Beech flour	20 g	40 g
Grain size	40 µm	120 µm
Demineralised water	200 ml	300 ml

Table 5: Levels table

We find below the construction design of experiments in table 6. The specified outcomes are the averages of measurements performed in tension on a family of three identical specimens. To summarize, we have three answers: the maximum strain in MPa named A, the modulus of elasticity in MPa, named B and rheological criteria assessed during the extrusion performed with a syringe, named C.

N°	**Ether starch (g)**	**Beech flour (g)**	**Water (ml)**	**Grain size (µm)**	**A (Mpa)**	**B (Mpa)**	**C**
1	40	20	300	40	7,30	719,0	2
2	40	40	200	40	2,69	289,0	3
3	10	20	200	40	0,16	21,6	2
4	40	40	300	40	1,01	113,3	3
5	40	40	200	120	0,53	65,0	3
6	10	40	200	120	0,31	45,6	3
7	10	40	300	120	0,01	2,00	2
8	10	20	300	40	0,29	39,33	1
9	40	20	200	40	1,11	98,33	3
10	10	40	300	40	0,01	2,00	2
11	40	20	200	120	2,49	274,3	3
12	10	40	200	40	0,41	64,3	3

13	10	20	300	120	0,00	0,0	1
14	40	20	300	120	3,81	332,6	2
15	10	20	200	120	0,30	52,0	2
16	40	40	300	120	1,17	160,6	3

Table 6: DOE construction

4.8 – Study effects

The relative importance of a parameter is estimated using graphs like those in Figure 2. The importance of the slope on each parameter gives information on the importance of the influence of this parameter. The more the factor's effect is important, the stronger the segment's slope is. It was therefore a means of quick visual assessment on the same graph of the relative influence of representative factors detailed in Figure 3.

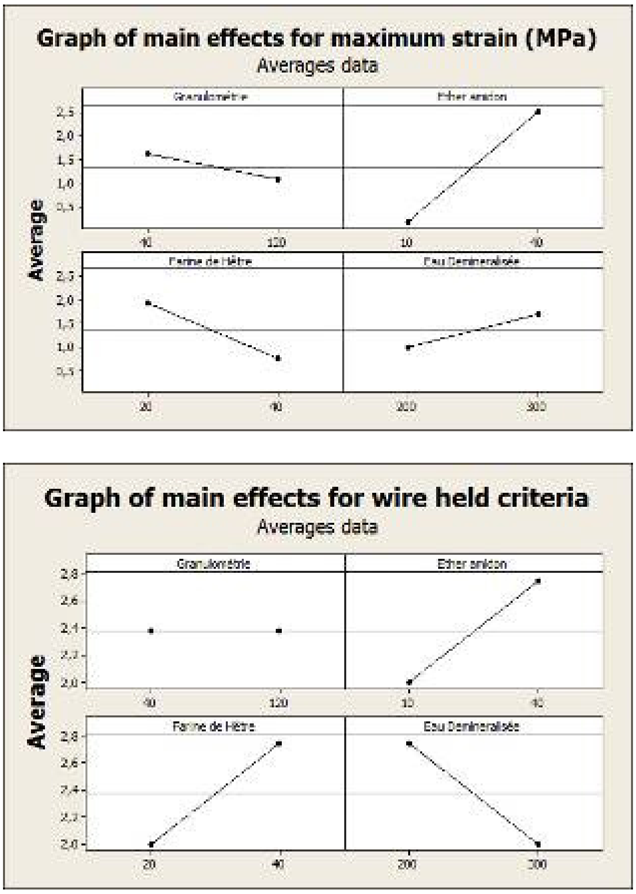

Figure 3: Graph of main effects

4.9 – Study interactions

An interaction between factors occurs when the modification of the response obtained on minimum level or on maximum level of a factor differs from the modification of the response on two identical levels of a second factor. In other words, the effect of a factor depends on another factor. You can use interaction diagrams to compare the relative strength of the effects of different factors.

We want to avoid the wire held during manufacture to meet the maximum geometric dimension of our shapes. We can study the factors affecting this behaviour.

4.10 – Optimization

The responses optimization function searches a combination of input variables that jointly optimizes a set of answers while satisfying the required conditions for each response of the set. To optimize the manufacturing conditions of our forms, we must define an individual desirability for each response. We must therefore increase our desire to obtain the best possible wire place during manufacture while maintaining a tensile high stress. We keep the goals while maximizing the responses.

The optimization diagram illustrates the effect of each factor on the responses or composite desirability. For the individual desirability we select a weight (between 0.1 and 10) to define the importance of the reaching of the target value. The composite desirability is the weighted geometric mean of individual desirability of different answers. The table summarizes the results and "best" configuration to simultaneously maximize our responses.

Composite Desir	*Maximum strain*	*Wire held criteria*
0,86	3,5 MPa	1,35

Grain size	*Ether starch*	*Beech flour*	*Water*
40 μm	40 g	**24,64 g**	**246,46 ml**

Table 7: Optimization responses

In our study, the composite desirability (0.86) is fairly close to 1, indicating that the settings seem to achieve favourable results for good performances of the thread during the manufacturing and it responds to using features.

5- Design Of Experiments Synthesis

Modified starch used is the most important factor affecting the tensile strength of the material. The flour beech fiber size may affect the resistance in our setup, contrary to what we thought. The starch needs enough water and does not need a high load of flour to achieve its characteristics.

For holding the wire on filing, it is more stable when the pulp is made up of less water and more flour. Starch is undeniably the invariant factor in our composition. The study shows that interactions of beech flour and starch have a strong responsibility to hold the wire in the presence of demineralised water. With the aim to improve our wood pulp, we headed towards the responses optimization to be closer to the best of our terms of use and manufacture.

6- Features integration towards design

6.1 – Method approach

In order to adapt the consumers' products design to the manufacturing process and to the material used, we want to integrate knowledge to link functional specifications to the product before its manufacturing. Manufacturability's analysis and application of guidelines to improve design solution are strongly related to a know-how linked to manufacturing problems. However, they do offer no real model of formal integration. This is done "mentally" on the originally defined product data (often geometric data) **[S1 and SR1].**

Data models have been proposed by several authors, which allow to model the design activity and to conserve a cooperative aspect between different actors that may intervene in the product's design. These models are related to design methods which, while remaining within the philosophy of concurrent engineering, have their own particularity **[SR1]**.

6.2 –Design parameters

According to the approach we must develop proposals that are adapted to each area depending on the product. For example, for manufacturing area, we can now specify that our product has a better geometrical stability (minimized collapse when the laying on the thread) using a paste according to the composition described in Table 7. It is a truth demonstrated by experiment, directly affecting the manufacturing features.

We know the sensitivity of our materials to moisture; we can define in the product's using space that objects will not be adapted to high humidity conditions. (below 70% RH depending on the characteristics of starch. For example, not in the external environment or in a bathroom), but our hygroscopic material remains mechanically and geometrically variable throughout its life, depending on temperature and humidity variations of its environment. We must add these parameters to the dimensional changes of our material after curing.

The relationship between feature and form is achieved through a grammatical approach generally to define a representation of a function by a noun-verb pair **[WM1]**. This representation should permit linking feature to form. This approach allows the definition of axioms and rules together with a specific vocabulary. All rules are still to be defined before they can be associated with the setting of a CAD model.

All these definitions will allow us to link design parameters to our product, or more precisely, to functions of manufacturing, use, or even recycling in end of life.

7- Conclusion and future work

We have to realize a study case using our design and manufacture method. It concerns a scotch-tape winder, which perfectly matches the consumers' products family. The importance of measuring the roughness of our material to foresee the friction of the rolling is all the greater that it will apply to our study case. One of our goals is to automate the manufacturing process.

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