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Molded Pulp Products Manufacturing: State of the Art

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Abstract

Eco-friendly packaging such as molded pulp products (MPPs) has gained commercial importance in recent years. However, this remains a greatly under-researched area and there is a real need to consolidate the best practices from research and industry, in order to increase its implementation. The goal of this paper is to describe the state-of-the-art in the MPP manufacturing. The description includes a classification of MPP, historical and recent applications, the production process and tooling characteristics, the main mechanical properties and the environmental sustainability. Throughout the article, focus will be placed on the thermoforming production method. In this context, an innovative drying technique that utilizes concepts derived from impulse drying technology is presented.

KEYWORDS: Molded pulp product, thermoformed molded pulp, environmental sustainability, impulse drying

1. Introduction

Molded pulp products (MPPs), also referred to as molded pulp or molded fiber products, are at present primarily used for the packaging of manufactured products or for food-related carriers, such as food containers and serving trays.

Due to form (geometry) and aesthetic limitations, MPPs have been restricted to the egg tray market for many years. However, demand is now increasing due to their sustainable qualities [1]. Being made of wood fibers, essentially cellulose, MPPs are in general, totally renewable and biodegradable. These qualities have enabled growing adoption within the packaging industry, with companies eager to embrace alternatives to oil-based forms of packaging due to government regulations as well as customer demands [2].

Increasing R&D effort with standardized design and testing practices is essential in order to meet the growing demand for eco-packaging with high quality features.

Reviews of historical development of industrial applications of molded pulp packaging, recent manufacturing innovations in the field and an overview of industrial scenario in the UK are given respectively in [1], [3], [4]. Fundamentals of the technology of manufacture of MPP is discussed also in [5], which dates back to 1966.

However, while these articles give great insight into historical and recent developments, the conclusions lack comparable quantification. Also, enough attention has not been given to thermoformed MPPs and there is a gap related to environmental considerations.

It was therefore necessary to conduct this comprehensive review containing quantitative collections of MPPs characteristics, starting from a unique categorization of production types, to the mechanical properties achievable in the product. This information is essential to understand the overall capabilities and limitations of MPPs, and to serve as a starting point for designers, engineers and scientists to conduct in-depth studies for application-specific requirements.

The goal of this paper is thus to determine the state of the art of MPP and an up-to-date review of research in this field. Throughout the article, focus is given on a specific type of manufacturing process, falling in the category of “*Thermoformed*” type of product. The technology involved in this category is more advanced than other processes, producing high quality, thin-walled items. In addition, being able to control process variables, such as pressure and temperature, enables the introduction of an innovative way of drying the products based on the concept of impulse drying.

This paper also provides an overview of the environmental sustainability of MPP. This includes the various life cycle stages, i.e. raw material extraction, production, use and end of life.

The paper is organized as follows. A classification of MPP, historical and recent applications are presented in Section 1.1 and 1.2 respectively. Section 2 discusses the manufacturing process, with focus on the *Thermoformed* products, and the different materials that were used to enhance specific product properties. Section 3 gives an overview of the tooling technologies available. The mechanical properties are presented in Section 4 while the environmental sustainability is discussed in Section 5. Finally in Section 6 the potential of the application of impulse drying concepts in the production of MPP is presented.

1.1 CLASSIFICATION OF MPP

Molded pulp describes a three-dimensional package that has been classified in different ways in the past years. The criteria used were based on the product density, on the production process and on the fabrication method [6].

The currently used classification comes from the International Molded Fiber Association (IMFA) [7] that categorizes MPP as follows:

1. *“Thick wall”*: manufactured using an open mold and then oven dried. Typical wall thickness ranges from 5 mm to 10 mm. The surface in contact with the mold is relatively smooth, while the other side is very rough. The raw material is typically Kraft paper mixed with recycled paper. They are usually used as support packaging for non-fragile, heavy items (e.g. furniture and vehicle parts).
2. *“Transfer molded”*: products in this category have thinner walls, 3 mm to 5 mm. They are manufactured using both a forming mold and a transfer or take-off mold. The result is a product with relatively smooth surfaces on both sides and better dimensional accuracy. The formed product is dried in a heated oven. The raw material commonly used is recycled newspaper. Typical examples are egg trays and packaging for electronic equipment.
3. *“Thermoformed”* (*“Thin-wall”*): this is the most recent approach. The initial formed product is captured in heated molds where it is pressed, densified and dried. No oven curing is needed. This process produces high quality thin-walled items (from 2 mm to 4 mm), with good dimensional accuracy, and smooth, rigid surfaces. The result resembles the appearance of thermoformed plastic items.
4. *“Processed”*: this refers to MPP that require some further or special treatment, for instance additional printing, coatings or additives [7].

The classification bring a greatly needed disambiguation, since publications on this topic often do not distinguish between the types of molded pulp process in focus.

1.2 HISTORY AND APPLICATIONS

In the mid-1800s, with the mass distribution of newspapers and books, the prices for paper-related products dropped, and thus new applications emerged. The first appearance of a method for making molded products from wood pulp dates back to 1890 [8].

The first patent for a machine for making pulp products was registered in 1903 by Martin L. Keyes, from Cambridge, Massachusetts [9]. Within a year, he had registered another patent with a structural improvement of the machinery [10].

Molded pulp was soon after used as packaging for eggs, designed and produced by the Canadian inventor Joseph Coyle, however the production machinery was not developed

until after the First World War. The shape of the package varied, and consequently the invention was applied to all sorts of fragile items, including light bulbs and fruit. The patent for this multi-use package was registered in 1920 [11]. Since then, the implementation of molded pulp products slowly increased, examples of other patented applications being a folding spoon for medicine, a pastry holder and packaging for a handset telephone (1940) [12].

The scenario changed in the late 1980s. In those years, consumers started to develop an interest in the environmental impact of the products that they were buying, so the molded pulp industry started to develop new and innovative solutions.

Currently, molded pulp is being used as a green statement by some industries and the applications are broader in many fields. Some examples of current applications have been already given above within the different product categories [1], [3]. In general, these products are related to three kinds of market, as it is shown in Figure 1.



Figure 1: Three main markets for MPP

Molded pulp is also used as a cushioning material for the protection of a product during transportation, e.g. molded honeycomb paperboard. With its high strength, durability and low cost, this material can replace wood and plastics [13].

In recent years, companies are creating environmentally sustainable practices and holistic products, often involving extensive use of recycled paper. Seventh Generation™ has

launched a new laundry-detergent bottle that uses molded pulp for the structural part of the container, while the detergent itself is contained in a plastic lining. In this way, the use of plastic is reduced by more than half [14]. Pangea Organics® packages soap in a clamshell made out of processed pulp which has plant seeds embedded in the packaging for planting on disposal [3]. Paper Water Bottle® has prototyped an eco-friendly replacement for plastic water/beverage bottles with a shell made entirely of renewable molded fiber, with an internal barrier that requires less plastic than a standard plastic bottle [15].



Figure 2: Paper Water Bottle® product rendering [15]

Tetra Pak® recently released a report [16] showing that consumers are seeking sustainable packaging, to the extent that it affects their choice of brands. This suggests that sustainable packaging is not just for the sake of the environment but also necessary for the sustainability of the brand.

The report *Packaging 2020* [17] provides a survey of the market scenario for 2020 for consumer packaging in general and wood fiber-based packaging in particular. As the world continues to urbanize, demand for packaging is likely to grow rapidly with a consequent need to develop an efficient recycling system. The growth of e-commerce will create a demand for standardized packaging sizes. Lifestyle trends towards convenience, health and environmental awareness will grow in importance for consumers. At the same time, the report indicated that national environmental legislations are getting stricter.

2. Process

While most paper-based packaging starts with flat sheets which are assembled into three-dimensional packages, MPP are made from cellulose fibers dispersed in water then formed, drained and dried [4].

The production process of the different molded pulp product types varies especially in respect of the drying method, which is usually performed in a heated oven.

In general, the production of molded pulp involves a water suspension of fibers being deposited onto a screened mold. A vacuum is then applied and the fiber-mat starts to develop some strength. Water can be removed by pressure applied to the slurry by means of a matched mold. After this phase, the molded preform usually reaches 50% in consistency (i.e. the mass fraction or percentage of solid in a given slurry) [18] and is then completely dried out in a heated mold or oven.

Manufacturing stages in the production of *Thermoformed* pulp products are listed here for clarification:

1. **Mixing:** the raw material is soaked in water and mixed until the desired pulp consistency has been achieved. Additives, such as sizing agents or fillers are introduced to produce the required functions, commonly utilized also in the papermaking industry [19].
2. **Forming:** the pulp part is formed to shape by custom designed tools. The tools consist of a metal net supported by a perforated mold. The machine is lowered into the slurry and the water is pulled through the metal mesh by applying a vacuum. The suction helps to bind the fibers.
3. **Pressing and drying:** the wet part is moved to a heated mold. The part is compressed, and dried completely by two matched halves of a mold. The surface becomes relatively smooth and good dimensional accuracy is achieved. The pressing also improves the mechanical properties of the product, aiding stacking and nesting for more efficient storage and shipping. Pressure is necessary to achieve good bonding between fibers. During this phase, vacuum can be applied when the part is pressed, thus removing excess steam and preventing related problems, such as delamination, which is defined as a drastic reduction in the z-directional strength of the product [20].
4. **Trimming and quality inspection:** protruding edges are trimmed and all the scraps or rejected products are returned to the pulp mixture and re-used. For specialty products, the produced parts can undergo some further processes, such as debossing or special treatments. The part is finally inspected for quality [21].

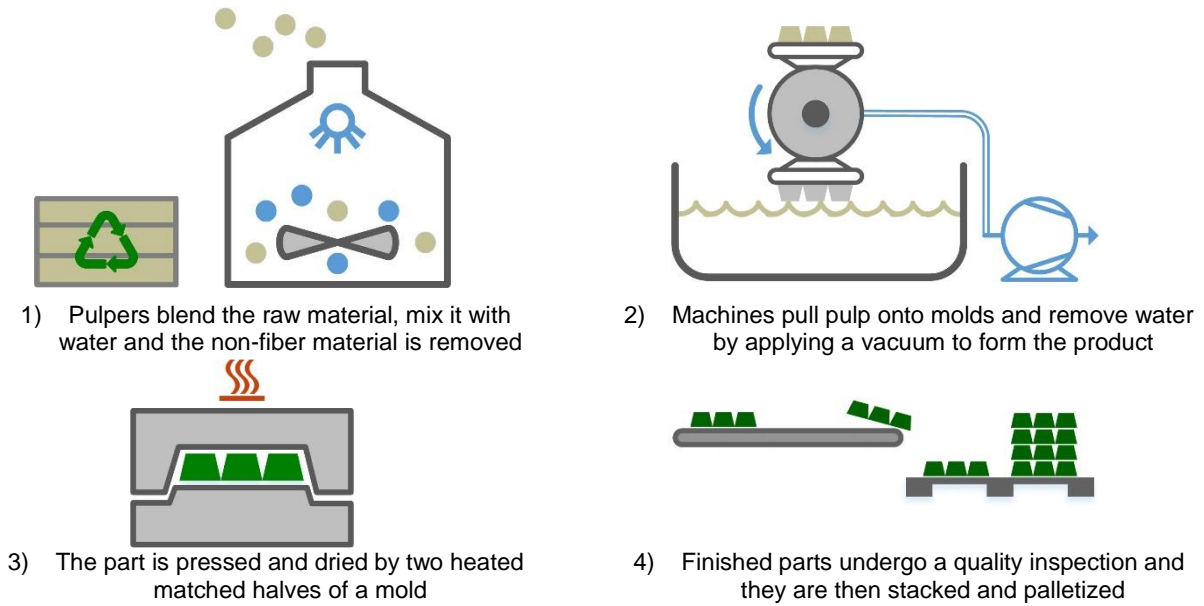


Figure 3: Manufacturing stages in the production of *Thermoformed* pulp products

2.1 PROCESS PARAMETERS

Regardless of the different combinations of raw materials that can be used for stock preparation, the processing conditions for MPP manufacturing are mainly characterized by the molding temperature, pressure and process time [22]. These variables are controlled based on the composition and consistency of the pulp used, and on its physical properties (e.g. temperature and viscosity). The process must be tailored with respect to the required appearance, dimensions and structural properties of the final product.

Limited work has been reported in literature on process implementation and controls, due to the fact that MPP are usually employed in applications that do not require high quality standards. Yokoi et al. [23] developed a bar-flow mold with pressure and temperature sensors and physically investigated the effects of different molding conditions. They found that the most significant factors were the mold temperature and the moisture content in the material. Sung et al. [24] optimized a pulp molding process virtually by means of computer simulation. They were able to show that it was possible to reduce the production cost of MPP by reducing the energy consumption during drying and did so by improving the forming systems.

2.2 MATERIALS

Molded pulp items are generally produced by mixing water with wood pulp made either from virgin fibers or recovered paper/paperboard, usually old newspaper, with a consistency commonly of 4% to 1% by weight. The pulp recipe depends mainly on the surface quality and stiffness properties required. However, other factors such as the pulp's sustainability and food/drug suitability (FDA) may place constraints on the recipe.

Several different types of pulp recipe can be used in the production of molded pulp, depending on the application. The selection of materials depends on the specific application, and recycled materials are often employed, such as old newsprint (ONP) and old telephone directories (OTD) [25]. Where required, water proofing properties can be altered by the use of additives. Dyes may also be added to produce specific colors.

Other non-conventional materials have been explored and innovative materials have been tried at the laboratory scale, such as coconut husk and natural latex. Partial combination with more environmentally friendly materials has been also considered. Method Company, for instance, is adding bamboo to the pulping process to create a stronger pulp. Bamboo is a fast growing plant and can be thus considered a sustainable virgin material [3].

Figure 4 summarizes the most relevant research in the context of the utilization of different material types in the production of MPP. The aims of the various investigations were different, with respect to the different materials added during the pulp preparation.

<p>Noguchi et al. [62]</p> <p>Combining shredded pulp with plastic microspheres and starch powder. Improved shock absorbing properties and reduced cycle time.</p>	<p>Sung et al. [63]</p> <p>Adding polyelectrolyte and changing pulp temperature. Improved water drainage rate during formation.</p>
<p>Gavazzo et al. [25]</p> <p>Varying pulp consistency and quantities of Old Newspaper (ONP) and flocculating agent. Establishment of reference values for the raw materials quality indices.</p>	<p>Cho et al. [64]</p> <p>Using unsorted Old Newspaper (ONP). Reduce raw material cost.</p>
<p>Park et al. [65]</p> <p>Mixing Old Newspaper (ONP) and Old Corrugated Container (OCC). Establish optimum mixing ratio of ONP and OCC.</p>	<p>Li et al. [66]</p> <p>Mixing Blast Furnace Slag (BFS) with waste pulp. Reduce the environmental impact of BFS.</p>
<p>Wang et al. [67]</p> <p>Modifying pulp fiber with chitosan. Improve dyeing properties.</p>	<p>Sridach et al. [6]</p> <p>Using sugarcane bagasse and binders. The experiments proved that MPP can be made with these materials.</p>
<p>Park et al. [43]</p> <p>Mixing Old Corrugated Container (OCC) with Empty Fruit Bunch (EFB). Controlling the water absorption rate.</p>	

Figure 4: Materials used for pulp preparation and affected properties, at laboratory scale

3. Tooling

Tool design is an important step in the MPP manufacturing process. In the first two patents for MPP manufacturing by Keyes [9], [10], the tool setup consists of two separate mold halves. At first, one half of the mold is dipped in a pulp slurry, the two halves are then matched and the pulp is compressed. Excess water is drained out of the mold by creating a suction pressure. Once the molded product is formed between the two halves of the tool, compressed air is used to release the final product. The molded part is finally put in an oven and dried.

The following points should be considered while designing tool for the production process:

- The tool must replicate the desired geometry of the final product.
- It should be able to produce desired surface finish on the molded product.
- It should be able to sustain a large number of stress cycles.
- The tool material should be corrosion resistant and inert towards the pulp slurry.
- The tool must be cleaned in between production cycles.

3.1 DYNAMIC COMPRESSIBILITY

Dynamic compression of the wet pulp inside the mold has a great influence on the final product [26]. Cellulose fibers in the wet web are entangled in a way that they make the entire structure porous. During pressing, two types of stress are generated in the web: stress due to fiber structure, which provides resistance to the flow of water in the web, and stress due to the hydraulic pressure. Terzaghi's principle [27], which is a phenomenon usually referred to in soil mechanics, states that the total stress anywhere in a porous medium is constant and is equal to the sum of the two stresses just discussed. Campbell [28] was the first one who applied this concept to paper forming, thereby verifying and quantifying the behavior of the wet web during the formation of paper. The stress applied during pressing gets counter balanced by the two stresses and the hydraulic pressure forces the water to be squeezed outwards.

The wet pressing process is influenced by the compressibility of the fiber network. Several researchers have studied the deformation of wet webs using a platen press [29], [30], [31]. In these studies, the paper web was compressed in-between a smooth solid material and a rough porous material. The expelled water was taken up by the porous material and transferred outwards by the drainage channels as shown in Figure 5.

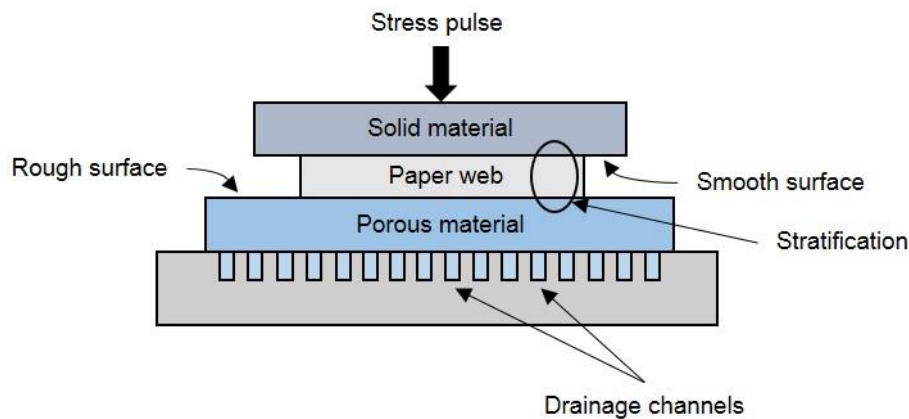


Figure 5: Characteristic of the tool setup for wet pressing

In this type of arrangement, water flows through the fiber network and experiences viscous forces. There is a decrease in hydraulic pressure due to the resistance offered by fibers to flow of water. The interaction between the viscous forces and the flow generates stress in the fibers. This structural stress accumulates and increases in the direction of flow. The interaction between fibers and the viscous forces also result in non-uniform and uneven compaction of the wet web in the thickness direction. This phenomenon is termed as *stratification* [32], [33].

The surface roughness of the porous material also influences the newly formed surfaces on the molded product. Dynamic compression of the wet web is largely affected if the permeable material has comparatively rough surfaces [34].

The force required to achieve complete compression is dependent on the structure of the surface of the permeable material. During compression, the water is not only squeezed out of the fiber network but also through the fiber walls. Vomhoff and Norman [35] in their studies indicated that the pressure should be directed towards the fiber and must be uniform throughout for avoiding uneven surfaces.

Complex geometries can be produced by designing the mold exactly of the same shape and dimensions as the desired finished product. It is also possible to control the surface parameters like roughness and texture of the molded product but it is essential that the mold should be made perforated to allow the dewatering from the paper pulp mixture.

3.2 MODERN TOOLING TECHNIQUES

Different design approaches are implemented for developing a tool setup for production of MPP. It's important to adopt a particular technique for production of tools as they help in reducing the downtime and lowering down the production cost of the paper product. Two such design techniques are discussed below:

Computer-Aided Engineering (CAE)

Manufacturing processes that require changing the molding tool or breaking the tool (like in sand casting) can lead to high production cost for the product. This can be solved by

implementing CAE and rapid tooling techniques in production [36]. The philosophy of rapid prototyping using CAE tooling requires a database to be created for generic pulp mold properties, all the properties such as wall thickness, height of structural unit etc. are inputs in the database. This helps the designer to identify the basic properties of a structural unit. Once the basic properties are known, a modular design approach can be implemented for production of the molded pulp packaging. The method is claimed to be better and more cost efficient than the conventional method of tooling processes for molded pulp packaging.

Tung-oil Sand Mold

In traditional proofing methods, the mold is designed and simulated in a computer software, which is then transferred to the machine, for making metal forming molds.

Wu et al. [37] introduced a new tooling process that aims at lowering the development cycle and reducing proofing cost. In their work, the authors studied tung-oil sand molds substituting the conventional metal molds. For a sand mold of thickness 10 mm, they suggested the required amounts of silica sand, tung-oil and bentonite. The mixture was grinded and then supplemented with treated fine-sand in a plaster mold, to make a cuboid sand mold sample. The sample had to be dried at a minimum temperature of 200°C. The mold can be produced in approximately 25 minutes. The results claim to speed up the development process, reduce cycle time and optimize the proofing costs.

4. Mechanical Properties

To promote the utilization of environmentally friendly packaging, such as MPP, requires an understanding of the basic mechanical properties. Properties such as tensile strength, compressive strength, bending stiffness, etc. play an important role in the assessment of the strength of the product. However, depending upon the application, the specific properties of interest will be tested during technical feasibility studies. Hence, the scientific papers usually refer to few specific features.

Paper is a natural material and is substantially affected by fibers length and environmental factors such as relative humidity and temperature, and its structural properties also depend on the drying rate. Therefore, deriving precise engineering equations for the design of paper-based structures is beyond current knowledge and design rules and experimentation must be tailored to the specific application addressed.

In the case of products for packaging, the properties typically of interest are the tensile and compressive strength for stacking and the variation in these values due to environmental conditions. MPP are often compared with those of a competing packaging material, expanded polystyrene (EPS). The comparison is made by measuring the cushioning effect, the energy absorption and the impact load carrying capacity [38]. Scientific efforts have been made in order to equalize the values achieved by the EPS products, thus offering a more sustainable alternative.

An exact definition of the mechanical properties of MPP is not possible, as the mechanical behavior of each sample depends on its size, on its particular geometry and on its wall thickness. The lack of control over dimensional tolerances in the manufacturing of cushioning products, leads to considerable variation in material strength and characteristics [39].

4.1 STRESS-STRAIN RELATIONSHIP

Ji et al. [40] employed a SEM (scanning electron microscope) to study the micro-scale mechanical behavior of MPP. The experimental results indicated that the material was not only elastic-plastic but also that it has viscous, or *emplastc*, characteristics. The strain distribution showed uneven characteristics due to the presence of voids, impurities and the random orientation and fractioning of fibers. The authors later published another research work investigating the stress-strain relationship of molded pulp material under certain conditions. Short span compressive experiments were carried out and the stress-strain curve was then fitted. With the increase of the strain-rate, the material responded with increased the ultimate strength but it maintained the same elastic modulus. The stress also decreased when the sample was unloaded, showing the so called stress relaxation behavior. This result confirmed that a non-linear *emplastc* stress-strain model can best describe the behavior of MPP [41]. The empirical model employed in this study was:

	$\sigma = G\left(\frac{\rho}{\rho_0}, \varepsilon\right)M(\varepsilon, \dot{\varepsilon})f(\varepsilon)$	(1)
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$G(\frac{\rho}{\rho_0}, \varepsilon)$ and $M(\varepsilon, \dot{\varepsilon})$ take respectively into account the effect of density and strain rate on stress. $f(\varepsilon)$ is a dimensionless function of the compressive strain and it reflects the buckling of the structure. ρ_0 is the reference density. The undetermined coefficients of the function were fitted using load-compressive experimental data.

The following graphs show the stress and strain curves for molded pulp in comparison with oriented paper board material. Data were collected from different papers. Molded pulp has been compared with an oriented paper board material because it has a similar density but it differs in the way is manufactured, in particular and like paper, it shows orthotropic behavior.

Figure 6 shows the tensile stress as a function of extension for molded pulp and paper board along both machine-direction (MD) (the direction the paper flows in production) and cross-direction (CD) (across the width of the paper). Table 1 summarizes the different methodologies and parameter settings, such as the rate at which the tensile test was carried out and the type of specimen used.

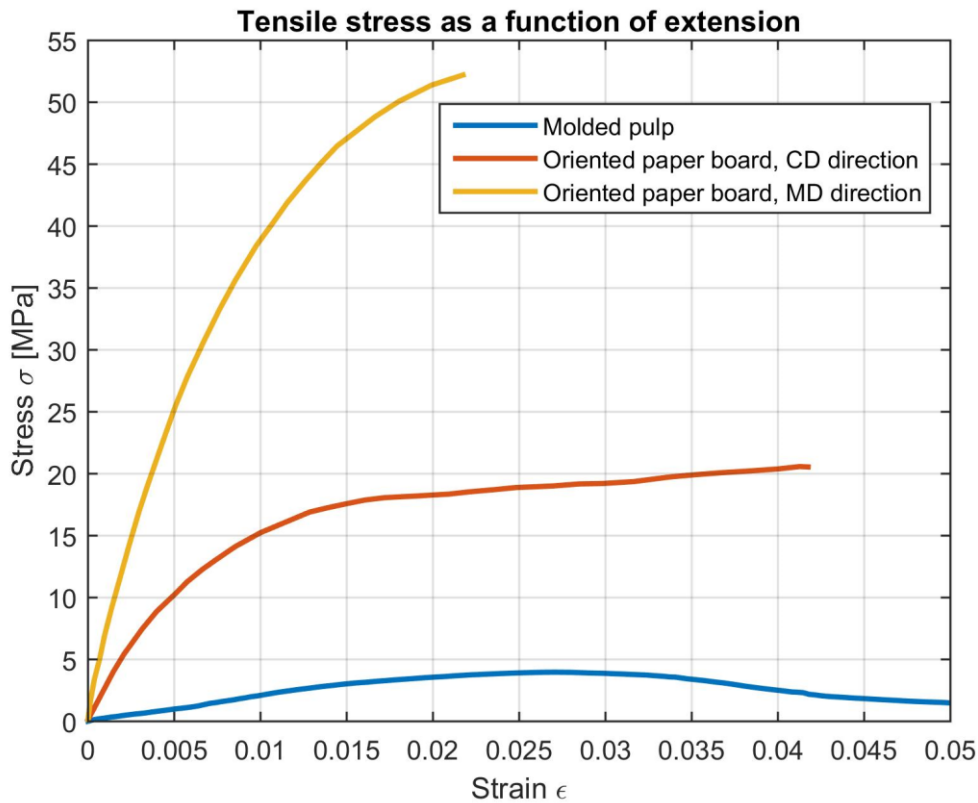
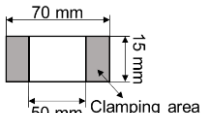


Figure 6: Tensile stress as a function of extension, comparison between molded pulp and paper board (CD: cross-direction; MD: machine-direction)

Table 1: Figure 6 parameter settings

Color	Researcher	Rate	Specimen	Density [kg/m ³]
Blue	Gurav et al., 2003 [39]	0,00167 s ⁻¹		350

Orange, CD direction	Fellers et al., 1980 [41]		Oriented paper board formed in a Formette Dynamique former using unbleached chemical pulp	590
Yellow, MD direction				

Figure 7 shows the compression stress as a function of compression strain. The comparison between molded pulp and paper board could not be made in the same graph because the strain of the paper board material is two orders of magnitude smaller. Table 2 lists the parameter settings.

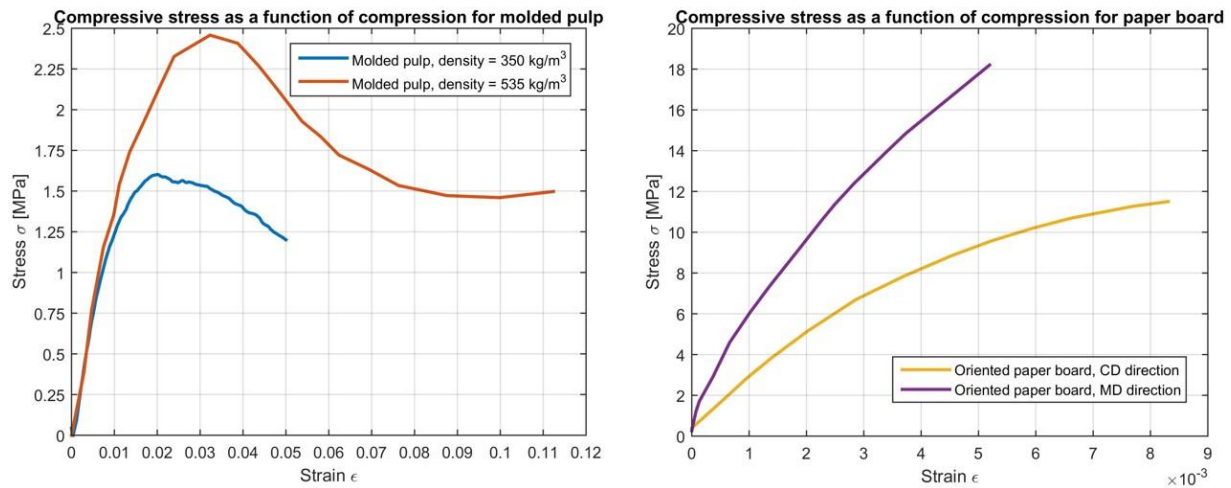
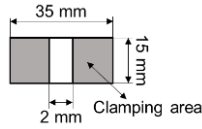
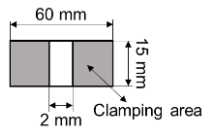


Figure 7: Compression stress as a function of compression for molded pulp (left) and paper board (right) (CD: cross-direction; MD: machine-direction)

Table 2: Figure 7 parameter settings

Color	Researcher	Test	Rate	Specimen	Density [kg/m³]
Blue	Gurav et al., 2003 [39]	Short span compressive test TAPPI standard T826	0,00833 s ⁻¹		350
Orange	Ji et al., 2010 [41]				535,2
Yellow, CD direction	Carlsson et al., 1980 [42]	Compressive test		Oriented paper board formed in a Formette Dynamique former using unbleached chemical pulp	590
Purple, MD direction					

4.2 CUSHIONING PROPERTIES

As stated in Section 4, the characteristic most often investigated is the cushioning property. Cushion curves are normally used to show the dynamic shock absorption ability

of a cushioning material. The method most often used to determine the shock attenuation is described by the standard ASTM D1596, *Standard Test Method for Shock Absorbing Characteristics of Package Cushioning Materials* [43]. The transmitted deceleration is plotted against the static loading (product weight per unit area), for a specific material type, thickness and drop height. Cushion curves are employed in the selection of the best combination of given materials that would be needed to protect a product with a particular fragility.

The shock absorption ability depends on several geometric factors and it can be tested with various methodologies. Table 3 gives an overview of the studies conducted to understand and measure the compression and cushioning properties of MPP.

Table 3: Cushioning and compression characteristics of MPP

Researcher	Properties investigated	Aim of the research	Type of analysis and parameters setting	Results
Eagleton et al., 1994 [44]	Cushion curves for molded pulp material	Comparison with cushion curves for EPS foam	Experimental analysis with different drop heights and static loading, with respect to four different pattern of molded dimples: two conical and two pyramidal	No significant differences between the different profiles were found
Sek et al., 2000 [43]	New method for the determination of cushion curves	The method proposed is capable of producing a cushion curve from the measurement of just a single impact, while it usually requires a large number of experimental data	The process involves an iterative minimization of the discrepancy between the values predicted from a theoretical model and the measured values	The approach allowed the determination of cushion curves from a small number of experimental data points
Hoffmann, 2000 [45]	Compression and cushioning characteristics of molded pulp packaging	The influence of the shape of the samples was examined. Rounded and squared geometry were compared	Samples with different density and thickness were used. The structures investigated were truncated cone and wedge shaped. Cushion curves and compression strength were obtained by using a drop test	Tests showed that axis-symmetric geometries, e.g. cylinders, have much better static and dynamic compression strength than squared ones
Wang et al., 2011 [46]	<i>Equivalent Area Theory</i> is proposed to study the cushioning properties	Verify the theory by means of simulation and experimental evidence	The theory required that the area considered when calculating the stress during a compression test is the cross sectional area of the dimples, and not the overall upper surface area of the sample. Simulations were performed with ANSYS® simulation software and then verified by static compression tests	By experimental and simulation analysis based on this theory the cushion curves for molded pulp pallet were obtained

4.3 DEGRADATION

An important aspect to be considered when dealing with packaging products is the ability to maintain constant stacking strength over time and when subject to changes in the environmental conditions.

There are many processes that can contribute to the degradation of molded pulp material, such as photo degradation, thermal degradation and biodegradation. Ou et al. [47] conducted a study to observe the variation of the mechanical properties of molded pulp containers after prolonged UV irradiation. The tests showed the reduction of the degree of polymerization by 50%, a decrease in weight of 10% - 16% and a decrease in the tensile strength of 10% - 30%.

Another important factor that can cause degradation is a change of the ambient relative humidity in which the products are stored. Moisture-induced effects on the stacking strength of molded-fiber packaging were studied by Sørensen et al. [48]. The authors observed that the compressional creep behavior resembled that of paper material and it was accelerated by humidity cycling (compared to constant conditions). The effect of temperature variation was also examined, by transferring the molded tray from cold storage to ambient conditions. It was concluded that condensation could induce a large initial creep deformation.

Compressive failures may also occur during the use of MPP. The failures are often due to buckling, and they develop from internal faults, such as impurities and voids. The random orientation of paper-pulp fibers makes it difficult to predict and determine the type and the location of the yielding.

5. Environmental sustainability

When discussing the environmental sustainability of molded pulp products, it is important to realize that they are part of a bigger product life cycle (Figure 8). This life cycle forms the basis for assessing the environmental sustainability of a product. Not only the production of the MPP, but also the sourcing of the raw material, use and disposal need to be considered. Many aspects of this life cycle can be relevant for the environmental impact, such as whether virgin or recycled fibers are used and if mechanical or chemical pulping is applied. This chapter addresses the main environmental considerations for each life cycle stage of molded pulp products, as well as the potential environmental impacts that can occur.

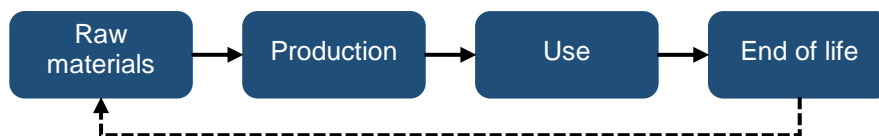


Figure 8: Life cycle stages of MPP

5.1 ENVIRONMENTAL IMPACT OF SOURCING RAW MATERIALS

Molded pulp products are mainly made from wood fiber, which is a bio-based resource, i.e. it is obtained from biomass. Wood fiber is also a potentially renewable resource, under the condition that the forests are properly managed. If this is not the case, the forests can be damaged, resulting in deforestation and/or loss of biodiversity in the area.

MPP can be made from virgin or recycled fiber, using the same production process. An advantage of using recycled fibers is that it reduces the number of trees that are needed and therefore the pressure on forests. In addition, the required energy consumption for creating a ton of recycled fiber pulp is 27% lower than that for virgin fiber pulp [49]. However, fiber recycling does require the use of various chemicals, for example for ink removal, such as colophony, paraffin emulsion, sizing wax resin and bauxite, which have an environmental impact of their own.

The quality of the fiber is affected in a negative way every time it gets recycled. How many times a fiber can be recycled depends on the wood species, the pulping process and the way the fiber is used in a product. In general however, the fibers can be recycled five to seven times [49]. The final fiber quality also depends on the quality of the waste paper source used for the pulp and can affect the performance of the MPP [50].

5.2 ENVIRONMENTAL IMPACT OF PRODUCTION

The two main techniques for pulping, mechanical and chemical, have different potential environmental impacts. Mechanical pulping has a higher yield, which makes the most of the forest resources, but is very energy-intensive. Kraft, or sulfate, chemical pulping results in paper with a higher strength, but requires 63% more chemicals than mechanical pulping. It also gives lower yields than mechanical pulping and can result in some

troublesome waste products [51]. It is therefore not straightforward which option is better from an environmental point of view.

A streamlined Life Cycle Assessment (LCA) by Das and Houtman [51] assessed the environmental impact of both the mechanical and Kraft chemical pulping process. The study showed that mechanical pulping has a significantly higher impact on global warming than Kraft chemical pulping. Kraft chemical pulping was found to have a significantly higher impact on acidification. The impacts on the other categories showed limited distinction.

The molding of the pulp into a product includes a drying process, which can require a high amount of energy. This is independent of the type of pulping process that is used. An LCA by Huo and Saito [50] shows that this drying process is an important contributor to the overall environmental impact. The precise environmental impact depends on the heat source that is used: steam showed lower impact results than heated air.

An important consideration from an environmental point of view is whether pulping and molding is done on an integrated production line or not. If the lines are not integrated, the pulp may be dried before it is transported to the location of the molding line. This requires additional energy on the pulping line and additional water on the molding line, which results in additional environmental impact. Alternatively, directly transporting wet pulp, without drying, increases the impact of the transport due to the additional weight and volume of the water. Both these issues are avoided on integrated production lines.

5.3 ENVIRONMENTAL IMPACT OF THE END OF LIFE

There are several disposal options for MPP. One option is to recycle them into other paper products. In order to achieve this, the products have to be collected and processed. The processing includes pulping, screening, refining, washing, drying and finishing [52]. As stated before, this has the benefit that the energy consumption for creating a ton of recycled fiber pulp is lower than that for virgin fiber [49].

Biodegrading or composting is another possibility for paper products, depending on the used additives, such as inks and adhesives. The environmental circumstances at the disposal site, such as access to oxygen and humidity, are very important for successful biodegradation [53]. If successful, biodegrading can provide a valuable by-product in the form of compost [52][54].

Another option is landfilling. A specific downside for landfilling paper products is that they can degrade anaerobically in a landfill, causing methane emissions. Since methane is a very powerful greenhouse gas, landfilling can be one of the main contributors to the global warming potential of paper products [52], [54]. Closed landfills that capture methane emissions can provide a solution to this.

5.4 ENVIRONMENTAL IMPACT COMPARISON WITH OTHER MATERIALS

Zabaniotou and Kassidi [55] used Life Cycle Assessment (LCA) to compare egg packages made from polystyrene and recycled molded pulp. In this study, the egg packages were

landfilled at end of life. While the results seem slightly favorable to the recycled molded pulp, the authors indicate that these results are not accurate and reliable enough due to a lack of available data. It was therefore not possible to provide a final conclusion on the matter.

Whether MPPs are a more environmentally sustainable option than other products can only be determined per application. This is because, for example, the amount of material needed and the end of life treatment will differ per application, for both the molded pulp product and the alternative. However, in general it can be said that MPPs have the potential to be environmentally sustainable. This results from the fact that they are biobased, can be biodegradable and are recyclable.

To ensure the lowest possible environmental impact, attention should be given to the contributing factors mentioned in the section discussing the various life cycle stages. For example, since landfilling can be one of the main contributors to the global warming potential of paper products [52], [54], this end of life pathway should be avoided as much as possible. Another attention point should be the energy use of the drying process [50].

6. Future Directions: Impulse Drying Technology for MPP

Manufacture

Impulse drying is a process in which water is removed from a wet paper web by the combination of mechanical pressure and intense heat. It was introduced in the beginning of the 1980s by Wahren [56] and it attracted considerable interest from the paper industry as a means of reducing energy consumption in the drying process. Despite over twenty years of research, this technology has never been applied in the paper industry. The reasons are linked to various operational problems that would affect the paper quality and thus the interest in this technique has waned.

In this process, the wet web is exposed to pressures ranging from 3 to 8 MPa and to hot surface temperatures typically between 100 – 350°C. The dwell or nip residence time (i.e. the time that the paper sheet remains in the press nip) is around 20 to 50 ms and it takes place in a so-called shoe-nip press, that replaces the conventional press nip [57].

Impulse drying is similar in nature to conventional wet-pressing operations but with applied heat. The applied heat has two main roles: it reduces the viscous resistance in the fluid phase and it softens the structure of the paper pulp, so that it becomes more compressible [58]. Within the moisture and temperature ranges of impulse drying, it is predominantly the lignin that is softened, as the other amorphous polymers (i.e. cellulose and hemicellulose) are always above their glass transition temperatures. Moreover, it was suggested that [58] if the heat transfer rate is sufficiently high, a vapor phase can be generated on the wet paper side in contact with the high temperature medium. This may assist in the dewatering process as the expanding steam can displace the bound water. This effect was studied and termed *flashing-assisted displacement dewatering* by Lucisano et al. [59].

Pilot scale experiments showed that some of the water present in the paper evaporates, and that some of it leaves the sheet in liquid form. This means that less heat has to be transferred resulting in a faster and a less energy consuming process [35]. The paper quality and mechanical properties were also enhanced by using this technique.

Understanding the mechanism of steam forming and its motion through a fibrous and porous medium such as paper pulp is difficult. The phenomena can be simplified and related to a class of heat transfer problems known as Stefan problems [60]. Considering a column of water being heated by conduction only from the top where a layer of vapor is forming, the solution to Stefan's problem in a one-dimensional domain is given by:

$$T_v(x, t) = T_H + \frac{T_s - T_H}{\operatorname{erf}\left(\frac{\varepsilon}{2\sqrt{\alpha_v}}\right)} \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha_v}}\right) \quad (2)$$

$$T_l(x, t) = T_0 + \frac{T_s - T_H}{\operatorname{erfc}\left(\frac{\varepsilon}{2\sqrt{\alpha_l}}\right)} \operatorname{erfc}\left(\frac{x}{2\sqrt{\alpha_l}}\right) \quad (3)$$

Where T_0 is the initial body temperature, T_H is the temperature of the heated medium, α is the thermal diffusivity of each phase (vapor and liquid), and ε is a constant related to the

rate of growth of the vapor phase with respect to the liquid. The velocity of the propagating interface ($\dot{h}(t)$) is found to be proportional to the square root of time ($\dot{h} \propto \sqrt{t}$) [58].

The introduction of impulse drying technology in the paper industry has been hampered by several operational problems. One such problem is delamination of the paper web, which is defined as a sudden reduction of the strength in the thickness direction of the paper. To prevent delamination, the fiber-to-fiber bonds must withstand the energy generated by the water, gases or steam moving in any direction during the impulse drying process [20]. The water permeability of the paper web is thus an important factor in controlling delamination. Low basis weight paper would facilitate the escape of flashed vapor out of the sheet without the occurrence of delamination [57]. Sheets with high basis weight would also delaminate more easily because of the existence of weak inter-floc bonds due to voids or impurities.

Another way to inhibit delamination consists of maintaining the pressure after opening the shoe-nip, allowing the paper to cool down without damaging the fiber-to-fiber bonds. This inevitably results in a longer process time and increased investment in equipment.

Re-wetting of the paper as it leaves the impulse drying unit could also occur if the water has not been effectively removed.

IMPULSE DRYING TECHNOLOGY FOR THERMOFORMED MPP MANUFACTURE

The application of impulse drying approaches to the manufacture of MPP was only recently reported [18]. In the production of *Thermoformed* items, experimental evidence showed promising results in terms of energy saving as well as reduction in process time.

The process and the technologies involved can be tailored and improved in order to satisfy the requirements needed to develop the *flashing-assisted displacement dewatering* effect.

The operational problems that the impulse drying technology has encountered could be controlled and overcome. One such problem is the time of contact with the heating element, needed by the paper pulp to achieve a certain pressure and temperature. In the manufacturing of MPPs there are not specific time constraints, unless the achievement of a certain throughput in a mass production scenario. To avoid delamination, the part could be kept inside a heated mold while vacuum is applied to remove the excess steam and water. This process that combines the traditional thermoforming facilities with the effect of an impulse technology has yet to be named and will therefore be referred to as *Pressure Flashing-Assisted Drying (PFAD)* for the remained of this paper and subsequent research.

The technology could be applied in the production of two-dimensional MPP and can be extended to the production of products with a three-dimensional closed geometry, as described in the patent application by Kumamoto et al. [61]. This patent describes the possibility of inserting an elastic and hollow pressing member inside the preform. A pressurizing fluid is then fed into the pressing member to inflate it, thereby developing a pressure onto the inner sides of the mold.

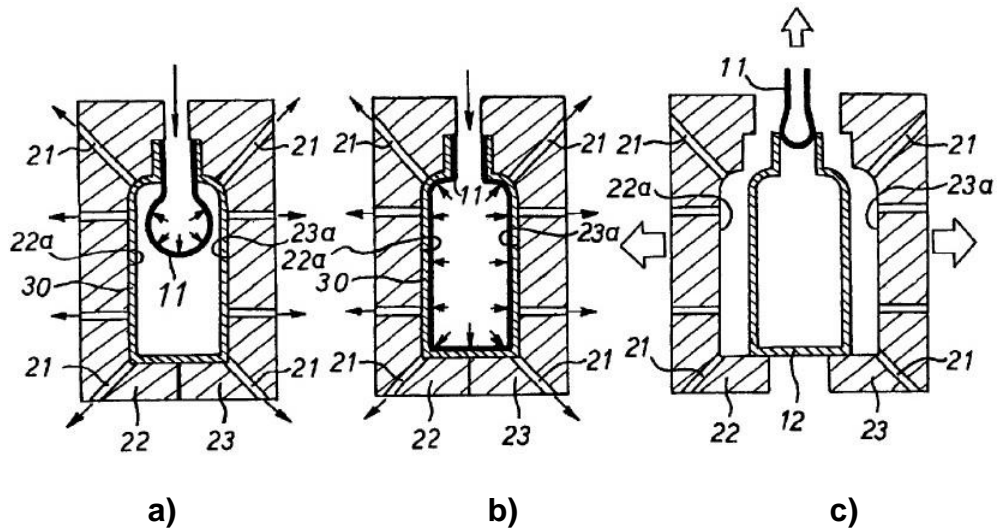


Figure 9: Patent application by Kumamoto et al. Cross sectional views showing the step of: inserting a hollow elastic body (a), inflating the elastic body and pressing the hollow container onto the inner wall of a heated mold (b), removing the elastic body and opening of the mold (c) [61]

PFAD has the potential to reduce the energy use in the drying process whilst simultaneously, increasing the production speed for thermoformed MPPs. The above tooling design show that *PFAD* is feasible not just for 2D MPPs but also for 3D closed geometries.

7. Conclusions

- An industry standard is required for performance testing of MPP forming processes and materials. The required first step would be to assess the tensile and compressive properties of standardized samples, along with their bending stiffness.
- Manufacturing techniques that use a wider range of raw materials are required, and other paper-based recycled items have to be identified as potential source material in the manufacture of molded pulp packaging.
- Tool design is an important step in the production of molded pulp products. Critical parameters such as wet pressing should be taken care of while developing the molds for MPP.
- Design guidelines for the whole process chain, for the tooling and the products, are required to make it easier to compare research results, share knowledge and shorten new molded pulp product development cycle.
- The long-term stability and final recovery of the material should also be examined [43].
- Molded pulp products have the potential to be environmentally sustainable. Whether they are the most environmentally sustainable solution depends on the specific application.
- The applicability of impulse technology during the drying phase of *Thermoformed* products should be further investigated. The packaging industry would benefit from such an improvement from a productivity point of view and it would also reduce energy consumption. This would enhance the green image of molded pulp. It would also increase product quality and performance. The speculation of the applicability of the *Pressure Flashing-Assisted Drying (PFAD)* has to be investigated by means of experiments.

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