

A MULTI-STAGE CASCADE USE OF WOOD COMPOSITE BOARDS

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ABSTRACT

A multi-stage cascade model was implemented on wood composite boards in four stages: particle boards → 100% recycling → middle density fibreboards → 100% recycling → paper liner. Preparation of composite boards bonded with urea-formaldehyde resin was simulated on plates 400 x 400 mm and final fiber was pulped using semi-production refiners to create the conditions closed to real. Mass changes and losses were observed during a whole simulated life process.

Results confirmed a deterioration of mechanical strength of recycled particle boards, the flexural strength in 13% and internal bond strength in 34% and slight increasing of the modulus of elasticity in static bending in 1.3%. Termomechanical pulping for the fineness in range 13°SR-24°SR (Schopper-Riegler) was chosen as appropriate for a fibrous board preparation from recycled chips, but their mechanical properties are at lowest levels compared to the requirements of standards. A low quality paper liner containing OCC, to improve its strength, was produced in the last stage of cascading.

KEYWORDS: Multi-stage cascading of wood, particle board, middle density fibre board, recycling, reuse, valorization of wood mass, paper liner.

INTRODUCTION

Cascading use as the efficient utilization of wood by using residues and material recycling to extend total biomass availability within a given system was executive summarized by European Commission in 2016. As it was concluded cascading at the market level can be quantified through wood flow analysis (Mantau 2015), also within one country (Babuka et al. 2020). A multi-stage

cascade use is the best option to valorize wood mass. In a single stage cascade, wood product is used once more for energy purposes; in the multi-stage cascading, this product is used at least once more, as materially recovered, before disposal for energy purposes or valorized according to principles of biorefineries (Pažitný et al. 2019).

Different methods can be used to reach this purpose. Reuse of postconsumer wood products (Singh and Ordonez 2016) is the initial point of responsible attitude towards wood resources and waste reduction as well. Combination of methods (reuse and recycling) could be also adapted from pulp and paper industry (Russ et al. 2013), but recycling of waste wood is the most common method applicable in practice (Ihnát et al. 2020). Means of chemical recycling (Balberčák et al. 2017, 2018), as well as means of mechanical disintegration (Ihnát et al. 2017, 2018), are used to obtain clear wood particles for new engineered products. Strong emphasis is being placed on the development of eco-adhesives (Antov et al. 2020, Petar and Savov 2019), both to facilitate recycling and from an environmental point of view, as well.

A wood-based panel and board production sector is one of the most important units in the wood processing industry with the total production of 59,2 million m³ in 2019 according to European Panel Federation. The massive part (32,1 mil m³) of it is formed by a production of particleboards, products with the highest recycle rate. More than one third of sources for their production is coming from recovered wood and this trend is still growing. Utilization of by-products also contribute in cascading (Mirski et al. 2020). The recovered wood is possible to obtain from demolition waste (Sakaguchi et al. 2016, Höglmeier et al. 2017) by simply pre-sorting a pure wood mass. But faster tailor-made identification methods are needed for more detail sorting to get a bigger portion of usable resource and to avoid the contamination of a new production (Faraca 2019). Waste wood pallets, drums and furniture represent a significant resource as well. Recycling of engineered wood may cause technical problems with shredding chips (Laskowska and Maminski 2020) or removal of impurities from recycled chips (Nuryawan et al. 2020), such less valuable wood can be used in the centre layers of new particleboards (Czarnecki et al. 2003).

Recycling of fibrous materials based on wood, as MDF and high density fibreboards (HDF), is connected to untying the bond between wood and cured glue. FT-IR results confirmed that the presence of urea formaldehyde (UF) resin residues on the surface of recycled fibers reasoned for deterioration in properties of recycled MDF boards (Moezzipour et al. 2017). Cured UF resin on the surface of recycled fibers can be also confirmed using SEM and XPS characterizations. For this purpose new processes for aqueous hydrolysis were developed containing weak acids (Lubis et al. 2018). A fiber length of the recycled fibers is shorter and the percentage of shorter fibers is higher for the former and finally, mechanical properties of recycled MDF are lower than those manufactured from a virgin fiber (Zeng et al. 2018). Substitution of other lignocellulosic materials (Ihnát et al. 2015) can significantly improve the total cascade balance for fibrous composite materials based on wood.

The purpose of this study is to demonstrate feasibility of cascading the hardly recoverable composites through an idea to recover wood mass in a sequence from bigger particle to smaller one (fiber). Conversion to “green” chemicals or an extraction of nano-crystalline cellulose (Irle et al. 2019) from waste fiber in the final stage is highly proclaimed, but an incorporation of paper product has been chosen by authors for this research. This incorporation could be a significant step to solve the current insufficient and unsatisfactory disposal capacities of waste MDF (Hagel and Saake 2020).

MATERIAL AND METHODS

The multi-stage cascade model of the wood composite boards use has been suggested (Fig. 1) according to the above mentioned definition and primary product (particle board produced of virgin chips) was materially recovered four times.

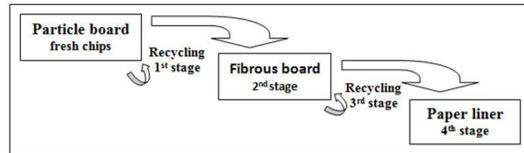


Fig. 1: Scheme of the multi-stage cascade model for a laboratory experiment.

Preparation of a primary particle board (PB) from virgin chips

Virgin wood chips obtained from a production plant (SK) were used for preparation of primary PB. Mix of softwoods (*Populus*) and hardwoods (mainly *Fagus sylvatica* and *Carpinus betulus*) was used in the ratio 1:1. The fraction of chips was determined by sieving (Tab. 1). The chips 0.2 mm - 2 mm and 2 mm - 4 mm were used for a surface and core of PB, resp.

Tab. 1: The fraction composition of chips used for the preparation of primary PB.

Comparative sample (stage 0)		
Sieve (mm)	Surface chips (%)	Core chips (%)
8	-	1.2
4	-	34.7
2	1.29	33.7
1	16.17	23.1
0.2	58.05	5.6
Residue	24.49	1.7

An adhesive mixture was applied to dried wood chips with moisture content of 5% in an adhesive applicator (Defibrator, SE). The adhesive mixture was composed of the urea-formaldehyde adhesive (UF) - Kronores CB 1100 F with addition of the 5% hardener DAM 390. A paraffin emulsion in the amount of 0.8% paraffin on the dry matter of chips in form of a 30% emulsion was added. The surface and middle chips are in a ratio of 1:1. Individual components of the adhesive mixture are equally represented for surface and center chips. The moisture content of chips in the matt before its compressing was 14.8% after application of the adhesive mixture. The formed chips matt was pressed in a press at temperature of 180°C for 230 sec. The resulted board was then formatted and air-conditioned.

Recycling of the particle board

The primary particle board disintegration

The initial destruction of primary PB was performed by size reduction to pieces about 10 x 10 cm. The pieces were cooked for 30 min to uptake their content of moisture. To disintegrate them, a drum chipper Pallmann equipped with longitudinal slits (length 54.1 mm, width 5.5 mm) was used. Chips were dried at 105°C and sieved. The fraction of chips prepared in the drum chipper was determined by sieving (Tab. 2).

The recycled particle board preparation

Recycled PB was prepared from 100% chips obtained from primary PB without adding of virgin chips. The same procedure, as the above mentioned, was used for applying the adhesive mixture. The adhesive mixture was composed of Kronores CB 1100 F with 5% hardener DAM 390. An amount of 0.8% paraffin on chips in form of 30% emulsion was added. The surface and middle chips are in a ratio of 1:1. The formed chips matt was pressed at temperature of 180°C for 230 sec. The resulted board was then formatted and air-conditioned.

Determination of mechanical properties

Mechanical properties of PB prepared from virgin chips, also recycled PB, were determined according to EN 310 (1993) (flexural strength and flexural modulus) and EN 319 (1995) (tensile strength perpendicular to the board- Internal bond). Properties were determined on Heckert FTZ 10/1. All mechanical properties were determined after boards' conditioning at 20°C and 45% humidity.

Preparation of a fiber board from the recycled particleboard*The recycled PB disintegration*

Chips were prepared from recycled PB, disintegrated to pieces 10 x 10 cm for 30, which were boiling in water for 30 min to achieve a min 40% moisture content (Ihnat et al 2017). The drum chipper Palmann with oval openings (5.5 mm, 54.1 mm) was used to prepare the chips. Distribution of the prepared chips was determined by laboratory sieving after drying at 105°C (Tab. 2). For fiber preparation, chips smaller than 2 mm were removed.

Tab. 2: The fraction composition of chips prepared from the 30 min cooking of primary/recycled PB bonded with UF resin, which were chipped on the drum chipper Pallman.

Cascading	(stage 1)	(stage 2)
Sieve (mm)	chips from primary PB (%)	chips from recycled PB (%)
8	-	12.4
4	19,3	30.3
2	20,3	15.4
1	20,7	22.4
0,2	25,6	17.6
Residue	14,1	1.9

Wood fiber preparation from chips obtained from recycled PB

Chips above 2 mm were heated to 80°C in water before grinding to achieve min 40% of the moisture content. A disc refiner Sprout-Waldron was also heated to this temperature. The chips were ground in a single pass through the grinding heads of the device. The obtained fiber with a fineness of grinding 5°SR (Schopper-Riegler) was insufficient for the needs of preparation of fibreboards. So the fiber was refined on Valley holander gradually 18, 40, 50, 70 min with increasing degree of °SR to 13, 24, 28, 40, resp.

MDF preparation from fiber obtained from recycled PB

A board with a thickness of 16 mm was made from the prepared fiber. An adhesive mixture was applied to a dried wood fiber with a relative humidity of 5% in an adhesive applicator (Defibrator, SE). The adhesive mixture was composed of urea-formaldehyde adhesive (UF) - Kronores CB 1100 F with the addition of 5% hardener DAM 390. It may contain a paraffin

emulsion in the amount of 0.8% paraffin on the dry matter of chips in the form of a 30% emulsion. The amount of 13% of adhesive mixture on the dry matter of the chips was used. After application of the adhesive mixture, the relative humidity of fiber in the mat before the carpet is being compressed was 16.3%. The formed fibrous mat was pressed at temperature of 180°C for 250 sec. The board was then formatted and air-conditioned.

Recycling of the MDF

Wood fiber preparation from MDF bonded with UF resin

The MDF was cut into 10 x 10 cm sections. These were boiled in water at atmospheric pressure with constant stirring for 3 min, until they reached a relative moisture content of at least 40%. The swollen parts of MDF were milled (one pass through) on the disc refiner Sprout-Waldron at temperature min 80°C.

A recycled MDF preparation

A board with a thickness of 16 mm was made from the recycled fiber under the same as the above mentioned conditions. The adhesive mixture was composed of Kronores CB 1100 F with 5% hardener DAM 390. The paraffin emulsion was added as well. The amount of 13% of adhesive mixture on the dry matter of the chips was used. The formed fibrous mat was pressed at temperature of 180°C for 250 sec. The board was then formatted and air-conditioned.

Preparation of a paper liner from recycled MDF

Pulp preparation

The recycled MDF was disintegrated to fiber by boiling in water, as mentioned above, and milled on the Sprout-Waldron under the same conditions. An amount of old corrugated cardboards (OCC), pulped in water (ratio 1:1) was added to a water mixture of wood fiber at 80°C. After mixing the components, the pulp was ground on a cone mill Jylha 0. The fiber produced was characterized by fractionation on Brecht-Holl fractionator. The fiber, pulp and mixture as well, was characterized by a dewatering time, amount of water retained (WRV), Schopper-Riegler grade (°SR) and defibrator grades (DS) (Tab. 3).

Paper liner preparation

The laboratory handsheets (160 g·m⁻²) were prepared on a Rapid Köthen sheet former according to ISO 5269-2 (2004). Samples were tested for an tensile index ISO 1924-2 (2008), tear index ISO 1974 (2012), burst index ISO 2758 (2001), air permeation resistance - Gurley method (ISO 5636-5 2003) for the determination of basic mechanical properties Tappi methods were used for determination of tensile strength (kPa), tensile energy absorption (J·m⁻²), and tear strength (m·N).

Tab. 3: Pulp properties.

Cascading			(stage 3)	
Sample		OCC	Wood fiber DS- 38	Mixture (1:1)
Schopper-Riegler (°SR)		50	13	37
Dewatering time (sec.)	500 ml	40.91	6.0	22.0
	700 ml	95.41	13.8	59.5
	800 ml	142.62	23.27	92.3
chips		0	7.76	0

Brecht-Holl	16	37.375	52.41	45.3
	50	22.330	19.47	20.92
	100	6.410	5.41	9.57
	-100	33.885	12.95	24.21
WRV (%)		130.9	95.7	114.8

RESULTS AND DISCUSSION

The model of a multi-stage cascade use of composite panels was laboratory implemented and evaluated on the every single stage as follow:

Preparation of the primary PB and recycled PB

Mechanical properties of prepared PB were determined according to EN 310 (1993): Wood based panels. Determination of modulus of elasticity in bending and of bending strength and EN 319 (1993): Particleboards and fibreboards. Determination of tensile strength perpendicular to the plane of the board. Final properties are showed in Tab. 4. The last column shows values required by EN 312-3 (2016): Particleboards. Specifications. Part 3: Requirements for boards for interior fitments (including furniture) for use in dry conditions.

Tab. 4: Properties of PB.

Cascading		(stage 0)	(stage 1)	
		Primary PB	Recycled PB	Standard (requirements EN 312-3)
Density (kg·m ⁻³)		650	650	-
Flexural strength (N·mm ⁻²)		21.51	18.79	13
Modulus of elasticity (N·mm ⁻²)		2291	2321	1600
Internal bond (N·mm ⁻²)		1.07	0.71	0.35
Thickness swelling	2 hod (%)	3.05	3.01	5
	24 hod (%)	7.87	6.98	10

As expected the recycling process caused deterioration of the main mechanical properties of PB. The flexural (bending) strength has been reduced from 21.51 N·mm⁻² to 18.79 N·mm⁻² and the internal bond (perpendicular to the plane of the board) strength from 1.07 N·mm⁻² to 0.71 N·mm⁻². The reduction represents 13%, and 34%, resp. But on the other side, the modulus of elasticity in static bending increased from 2291 N·mm⁻² to 2321 N·mm⁻² which represents the increment of 1.3%. Similar results achieved Lykidis and Grigoriou (2008) after hydrothermal recovering the particles under a low pressure and temperature 119°C. They also found that after the second hydrothermal recycling under pressure (8 bars, 167°C, 20 min) the modulus of elasticity has been increased by 20.7%. It is evident that chips during a hydrothermal treatment, which is needed to separate them from each other, pass to the higher elastic stage depending on the strength and duration of the treatment. A higher elasticity may cause reduction of long-term deflections of boards in service.

Preparation of a fiber board from recycled PB

The composition of chips from recycled PB (Tab. 2) has a high proportion of fine chips below 2 mm, so the amount of usable chips for fiber preparation represents only 58.1% (sieve 2,4, and 8). The obtained fiber with a grinding fineness of 5°SR is insufficient for preparation of MDF (Tab. 5), due to the high proportion of fiber 16 (40 mesh) in comparison with fibers from the boiled MDF (comparative sample). Therefore, refining on Valley holander gradually 18, 40, 50, 70 min with increasing degree °SR 13, 24, 28, 40 was provided.

Tab. 5: Distribution and properties of fiber from waste PB after the 30 min cooking and grinding on the Sprout-Waldron mill and additional refining on the Valley-holander.

Cascading		(stage2)					Comparative sample MDF
Method of fiber preparation		Sprout-Waldron milling	Sprout-Waldron and Valley holander refining				
°SR		5	13	24	28	40	10
Milling time		-	18 min	40 min	50 min	70 min	-
Dewatering (sec.)	500 ml	1.66	2.47	12.46	14.25	19.47	2.25
	700 ml	2.60	4.70	21.38	26.73	49.19	3.05
	800 ml	3.02	9.50	28.00	38.66	74.92	3.35
Brecht-Holl (%)	Chips	0	0	0	0	0	4.243
	16 (mesh 40)	67.18	42.52	25.90	20.15	4.175	47.207
	50 (mesh 120)	18.82	40.56	47.48	48.04	49.330	24.295
	100 (mesh 240)	10.76	10.13	13.47	16.12	19.490	15.970
	+ 100 (mesh 240)	3.23	6.79	13.15	15.73	26.805	8.285

The fiber distribution (Tab. 5) shows a good agreement in the amount of rough fiber 16 (40 mesh) and a higher value of the middle fine fiber 50 (120 mesh) at 13°SR. Fine fiber fractions are in a good agreement as well. The content of 4.2% of chips of the comparative MDF indicates it's not completed decomposition. At 24°SR (grinding for 40 min), the major part of fibers is shifted from rough to medium finesses. The percentage of fine fibers is in a good agreement with the comparative sample. The shift of the fiber distribution is also evident by the dewatering (retention) time, which increases with the decrease of the fine fibers fraction. This implies the possibility of grinding the chips into fibers in the range of 13°SR - 24°SR for the production of MDF from recovered chips. The fiber 28°SR - 40°SR would require more adhesive to prepare MDF, as it contains more dust particles. Termomechanical pulp from recycling boards are of shorter fibre length and higher content of fine fraction (Roffael et al. 2010). Boards prepared from fiber with 13°SR have the properties as showed in Tab. 7 (stage 2).

Recycling of MDF

The fiber obtained after grinding on the disc refiner Sprout-Waldron by one pass through the device was characterized by a dewatering rate and the Brecht-Holl fractionation. The obtained parameters are in a good agreement with the comparative MDF. The obtained fiber is sufficient without a further processing to prepare new MDF.

Tab. 6: Distribution and properties of fiber from waste MDF after 3 min of cooking and grinding (one pass trough) on a disc refiner Sprout-Waldron.

Cascading		(stage 3)	
Method of fiber preparation		Sprout-Waldron milling	Comparative sample (MDF)
°SR		12	10
Dewatering (sec.)	500 ml	2.12	2.25
	700 ml	6.21	3.05
	800 ml	10.18	3.35
Brecht-Holl (%)	Chips	0	4.243
	16 (mesh 40)	42.11	47.207
	50 (mesh 120)	34.78	24.295
	100 (mesh 240)	12.13	15.970
	+ 100 (mesh 240)	10.98	8.285

After weekly conditioning at 20°C and HC 45%, the properties of prepared MDF are listed in Tab. 7. The table also contains the required values according to STN EN 622-5 (2010): Fibreboards. Requirements for dry board (MDF). Flexural strength and flexural modulus of elasticity were determined according to EN 310 (1993), and tensile strength perpendicular to the plane according to EN 319 (1995).

Tab. 7: Properties of fibre boards.

Cascading		(stage 2)	(stage 3)	Standard (min. value) STN EN 622-5
		MDF	Recycled MDF	
Density (kg·m ⁻³)		720	720	-
Flexural strength (N·mm ⁻²)		22.15	21,98	20
Modulus of elasticity (N·mm ⁻²)		2284	2208	2200
Internal bond (N·mm ⁻²)		1.12	1.03	0.55
Thickness swelling	2 hod (%)	3.05	4.45	5
	24 hod (%)	7.87	9.8	10

The flexural strength of fully recycled MDF (stage 3) has been reduced from 22.15 N·mm⁻² to 21.98 N·mm⁻², modulus elasticity from 2284 N·mm⁻² to 2208 N·mm⁻² and internal bond strength from 1.12 N·mm⁻² to 1.03 N·mm⁻². These reductions represent up to 8% only, but the mechanical properties of MDF (stage 2) produced from fibers obtained from recycled chips are on a bottom level comparing to standard requirements (Tab. 7). Roffael et al. (2010) stated that termomechanical pulp obtained from recycling boards can be used up to 30% as a partial substitute for pulp from wood in making UF-bonded MDF without any noteworthy deterioration of the physical-mechanical board properties.

Preparation of paper liner from recycled MDF

The strength properties were determined on the laboratory prepared handsheets Ø 220 mm (Tab. 8). Mechanical properties of paper liner made of termomechanical pulp obtained from recycled wood composites and mixed with OCC are lower as from semichemical pulp obtained from the same material (Balberčák et al. 2017). Additional treatment can significantly improve their mechanical properties, also their resistance to oil and grease (Gigac et al. 2018).

Tab. 8: Properties of the paper liner.

Cascading	(Pažitný et al. 2013)	(stage 4)
Basic weight ($\text{g}\cdot\text{m}^{-2}$)	-	164
Thickness (μm)	129	459
Bulk density ($\text{cm}^3\cdot\text{g}^{-1}$)	-	0.36
Tensile index ($\text{N}\cdot\text{m}\cdot\text{g}^{-1}$)	36-93.25	33.2
Burst strength (kPa)	160	156
Burst index ($\text{kPa}\cdot\text{m}^2\cdot\text{g}^{-1}$)	2-5.85	1.8
Air permeation resistance (Gurley method) (s)	9.3-22.34	6.1
Tensile energy absorption ($\text{J}\cdot\text{m}^{-2}$)	43	74
Tear strength (m-N)	485	620
Tear index ($\text{m}\cdot\text{N}\cdot\text{m}^2\cdot\text{g}^{-1}$)	4.4-6.10	5.6

Pažitný et al. (2013) have reached similar values for liners made from energetic grasses mixed with OCC. The strength properties of the liner prepared in this study are lower compared to the properties of the wrapping paper, but the paper is consistent and is more suitable for the practical use in higher basis weights, e.g. as pads, underlay bases, paper for separating the layers of material/goods from each other etc.

CONCLUSIONS

The cascading use of wood takes place in many forms. Recycling as the most usable form of material recovery is hardly realizable for wood based composites. To realize its full potential, barriers to cascading need to be overcome. Fiber shortening, glue residual stickled to wood particles and deterioration of mechanical properties are accompanying features of the recycling process. This article presents one way of a multi-stage cascade model for wood composite boards bonded with UF resin, where the principle of recycling “the bigger sized particle to smaller” was applied. The results confirmed a well-know knowledge that the mechanical properties of recycled products are lower than that from virgin wood. The last stages of cascading in this material flow showed that properties are at the lowest levels of properties required by valid standards. Hydrothermal recovery of particles and termomechanical pulping are important processes in a valorization process of wood mass but at the cost of reduced mechanical properties. Low cost paper liner could be a solution for the final stages of cascading of glued wood based composites, but wider research is needed.

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