

Techno-Economic Analysis of Simplified Microcrystalline Cellulose Process

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This work presents a techno-economic analysis of two modelled microcrystalline cellulose (MCC) production facilities, a stand-alone mill, and a mill integrated into a chemical pulp mill, with annual production levels of 30,000 tons/year. These results indicate that both options can be very profitable when the return on investment and the added value of the purchased chemical pulps are used as indicators. However, the integration of MCC production will yield about 19% greater net profit than the non-integrated alternative. Integration also reduces the economic risk of investment, since operation of the MCC plant can be halted for maintenance and chemical pulp can be produced in a normal manner.

Keywords: Microcrystalline cellulose; Stand-alone plant; Integrated plant

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INTRODUCTION

Microcrystalline cellulose (MCC), specified in E460, is a versatile product in many industrial applications, including pharmaceuticals (stabilizing, texturing, and tableting) and food (food and beverage texturing agents and dietetic substances). In smaller quantities, MCC is used in oil drilling, paints, cosmetic products, heat shields, and even flame-resistant board (Tuason *et al.* 2009).

Microcrystalline cellulose is a flour-form cellulose product that can be manufactured from all types of natural celluloses (Battista and Smith 1962). Adel *et al.* (2010) used rice and bean hulls for MCC manufacturing, El-Sakhawy and Hassan (2007) bleached kraft bagasse pulp and bleached soda rice straw pulp, Elanthikkal *et al.* (2010) banana waste, Haafiz *et al.* (2013) oil palm residue, Ilindra and Dhake (2008) bagasse and rice straw, Kalita *et al.* (2013) yellow foxtail, Kazakova and Demin (2009) unbleached kraft pulp, Nada *et al.* (2009) cotton linters, and Trache *et al.* (2014) esparto grass. The Food and Agriculture Organization of the United Nations (FAO 1996) defines MCC as “purified, partially depolymerized cellulose prepared by treating alpha-cellulose, obtained as a pulp from fibrous plant material, with mineral acids. The degree of polymerization is typically less than 400 and not more than 10% of the material has a particle size of less than 5µm”.

The world annual production of MCC is about 100,000 tons (Ciechanska *et al.* 2010). However, the production of MCC is very modest when compared to the annual production of 4.2 million tons of dissolving pulp (Sixta *et al.* 2013) and 128 million tons of paper pulp (FAO 2011). Both of these volume grades can also be used as a potential raw material for MCC manufacturing.

Several methods have been proposed for the production of MCC. The following sources cover processes in which the cellulose as a form of dissolving or paper pulp is

hydrolyzed by using chemical processes (Battista *et al.* 1961; Gospodinov *et al.* 1976; Cruz 1983; Bergfeld and Seifert 1996; Milford *et al.* 2001; Trusovs 2001; Guo *et al.* 2002; James *et al.* 2003; Kopesky *et al.* 2004; Ioelovich and Leykin 2005; Luo and Neogi 2006; Nguyen and Tan 2006; Frangioni and Frangioni 2010), enzymatic processes (Zabriskie 1984; Townsley 1988; Braunstein *et al.* 1994;), hydrothermal processes (De Long 1989; Ha and Landi 1998; Chornet and Jollez 1999; Brinkman and Schaible 2003; Chornet *et al.* 2006), or a combination of these (Dobashi *et al.* 1992; Yaginuma *et al.* 1996; Nguyen 2006; Schaible and Sherwood 2005; Frangioni and Frangioni 2012). From this process or process concept mentioned above, mineral acid hydrolysis with hydrochloric acid (HCl) or sulfuric acid (H₂SO₄) has become a “state of the art” manufacturing method, covering most of the MCC production today. However, even mineral acid hydrolysis methods have features that prevent economic and environmental-friendly production of MCC. These shortcomings, based on patent information (because actual plant data is not available), can be listed as follows: (a) high acid consumption (10 to 200% of raw material dry weight) (Battista *et al.* 1961; Gospodinov *et al.* 1976; Cruz 1983; Yaginuma *et al.* 1996; Guo *et al.* 2002; Ioelovich and Leykin 2005; Schaible and Sherwood 2005); (b) long retention times with low acid doses (several hours) (Frangioni and Frangioni 2010); (c) low reaction consistency (1 to 4%) (Battista *et al.* 1961; Guo *et al.* 2002); (d) high need of a neutralizing agent (Battista *et al.* 1961; Gospodinov *et al.* 1976; Cruz 1983; Yaginuma *et al.* 1996; Trusovs 2001; Guo *et al.* 2002; Ioelovich and Leykin 2005; Schaible and Sherwood 2005; Nguyen and Tan 2006); (e) high volume of effluent with high chemical oxygen demand (COD) (Battista *et al.* 1961; Gospodinov *et al.* 1976; Cruz 1983; Zabriskie 1984; Braunstein *et al.* 1994; Yaginuma *et al.* 1996; Trusovs 2001; Guo *et al.* 2002; Schaible and Sherwood 2005); and (f) no recovery of used chemicals (Battista *et al.* 1961; Cruz 1983; Gospodinov *et al.* 1976; Dobashi *et al.* 1992; Yaginuma *et al.* 1996; Milford *et al.* 2001; Trusovs 2001; Guo *et al.* 2002; Ioelovich and Leykin 2005; Kopesky *et al.* 2004; Nguyen and Tan 2006; Frangioni and Frangioni 2010; Frangioni and Frangioni 2012).

These reasons have led to the small-scale production of MCC, *i.e.* less than 10,000 Bone Dry tons per year (BDt/yr), with only a few companies in the market. Due to this development, the price of MCC has been fairly high at 4,000 to 10,000 € per Air dry ton (ADt) (pricing obtained from an anonymous Nordic retailer) and is highly dependent on product particle size distribution and purity. The high price and limited availability have restrained the commercial end uses of MCC on a wide scale.

To promote the bio-economy of the world, Aalto University in Espoo, Finland, has developed a new MCC manufacturing process (Dahl *et al.* 2011a; 2011b), by which MCC can be produced with low acid consumption using a short reaction time and a high reaction consistency (Vanhatalo and Dahl 2014). Using these flexible process conditions, relatively narrow particle size distribution can be achieved with precise end-product quality (degree of polymerization (DP), viscosity, and yield). The need for a neutralizing agent is also low due to low concentration of the acid used in the process. In addition, this approach enables the use of different pulp grades (unbleached, semi-bleached, or fully bleached pulp) as a raw material, which can be refined for a much broader application area than traditional MCC.

This study focuses on the techno-economic analysis of MCC production for the two-modelled process concept, a stand-alone MCC plant (sMCC) (Dahl *et al.* 2011a) and a MCC plant integrated into a chemical pulp mill (iMCC) (Dahl *et al.* 2011b). When the analysis process is defined, the operational and total project costs of the two process options

of MCC manufacturing are assessed with the aim of an economic cost-benefit analysis. Finally, the profitability and the added value for the bleached kraft pulp is defined.

EXPERIMENTAL

Technology

In this two-modelled process concept, one MCC plant provides the sMCC study, while another MCC plant is integrated into the chemical pulp mill iMCC study. The default balance calculations for each case study is presented in Table 1.

Table 1. Default Values for Balance Calculation

	Unit	sMCC case	iMCC case
MCC production, C_{Mp}	BDt/yr	30000	30000
MCC yield, C_{My}	%	90	90
Pulp consistency, C_{cons}	%	90	30
H ₂ SO ₄ dosage, $C_{A\%}$	%	1.5	1.5
H ₂ SO ₄ water, C_{Aw}	t/yr	680	680
Hydrolysis consistency, C_{Hyd}	%	30	30
Wash water amount, C_{Wwa}	t/yr	15000	15000
MCC dry matter after dewatering, C_{Dw}	%	50	50
MCC dry matter after drying, C_{Dr}	%	90	90

The production level 30,000 BDt/yr for the two process options has been chosen according to the existing applicable markets, 100,000 t/yr (Ciechanska *et al.* 2010). In both cases, the used raw material is a bleached softwood kraft pulp, the process water is chemically purified water, and the acid is the liquid form of H₂SO₄.

The process conditions are based on the laboratory experiments presented by Vanhatalo and Dahl (2014). The hydrolyzing agent, H₂SO₄, is chosen because hydrolyzate from the iMCC process can be recovered in the recovery plant of a chemical pulp mill. The acid dosage is 1.5% (based on dry raw material), the hydrolysis consistency is 30%, the process temperature is 160 °C, and the hydrolysis time is 10 to 15 min. These parameters provide a 90% process yield and produce an average MCC size of 20 µm.

Stand-alone MCC plant

Figure 1 shows a simplified flow chart of the sMCC case.

In the sMCC case, pulp raw material is imported to a mill in dry bale form (90% consistency). The bales are first disintegrated during the shredding stage with a shear shredder (Woodruff 1986), where a certain amount of water is added. The shredded pulp suspension is transferred to the hydrolyzing stage by a screw conveyer (Perry *et al.* 1984), where acid is added just prior to hydrolysis. The hydrolysis stage is carried out in a continuous screw reactor (Biermann 1993; Brännvall 2007). This reactor type was selected because the screw reactor has a simple structure, allows continuous processing, provides a production rate that is easy to adjust by changing the screw rotating speed, and allows high consistency in the hydrolysis stage which is suitable for the reactor type. The heating of

the reactor is carried out using direct steam heating, with steam generation in a bio fuel boiler using natural gas as a fuel. The natural gas and process electricity are imported to the mill site.

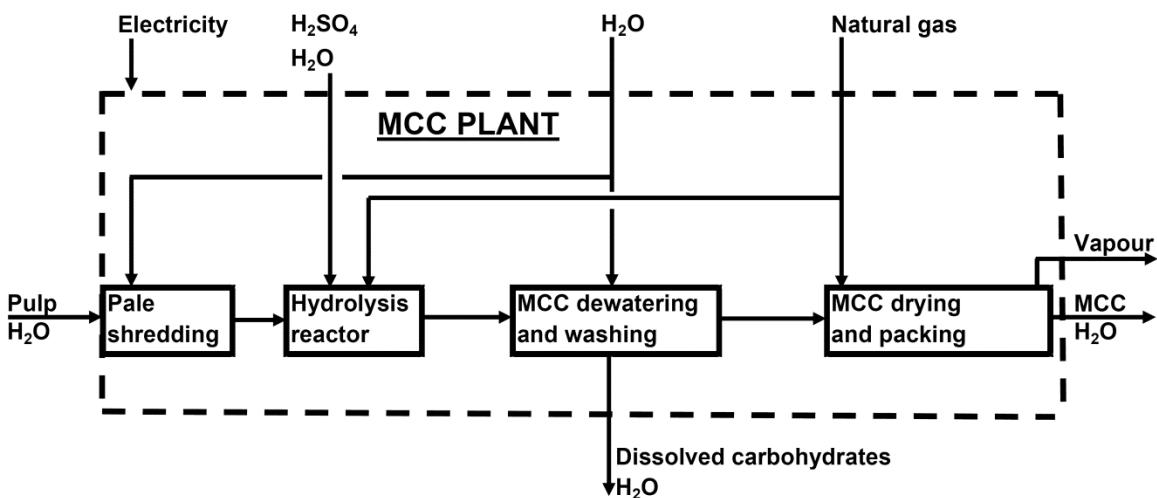


Fig. 1. Flow chart of the sMCC case

After hydrolyzation, the product is dewatered and washed to attain a dry matter content of 50%. The high 50% dry consistency is possible to gain because the fiber structure of cellulose is destroyed and solid MCC particles are formed. Therefore, the dewatering of the MCC particles is efficient. Dewatering and washing is performed with a decanter centrifuge (Perry *et al.* 1984). The MCC is dried to a consistency of 90% by using a flash dryer (Gullichsen and Fogelholm 1999a). Process water and H₂SO₄ are supplied to the mill. The MCC is packed after drying into flexible intermediate bulk containers.

Further processing and neutralizing of the hydrolysis filtrate is excluded from the sMCC process calculations, which is why waste water treatment is not included in process figures. Since the raw material of the process is bleached pulp, the filtrate consists of only dissolved carbohydrates without any extractive which can inhibit further processing. This reason gives the opportunity to utilize the filtrate stream for various purposes like fermentation to produce bioethanol or other processes to produce various biochemicals.

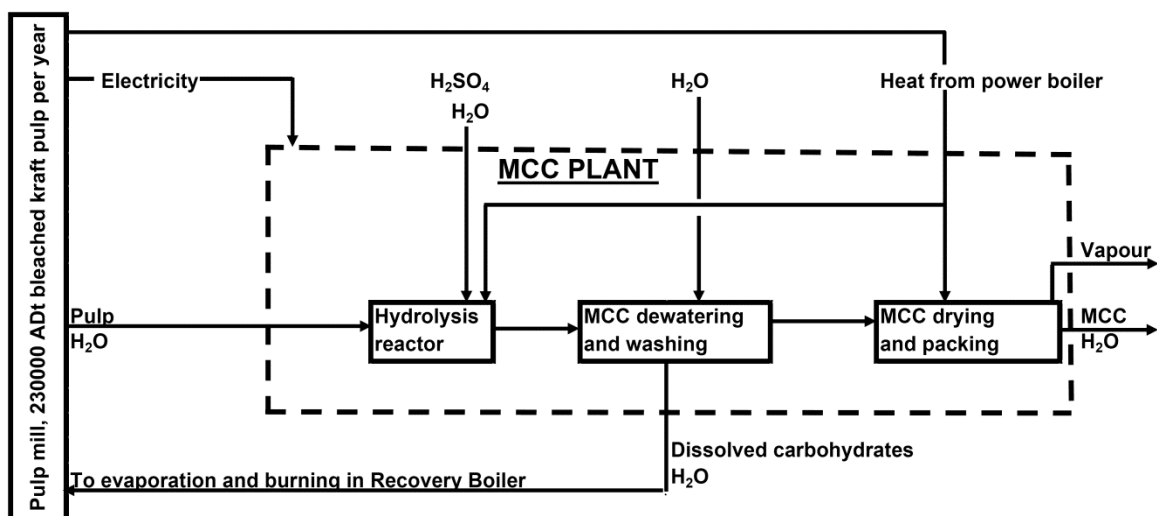


Fig. 2. Flow chart of the sMCC case

MCC plant integrated into the chemical pulp mill

Figure 2 shows a simplified flow chart of iMCC with a capacity of 30,000 BDt/yr that is integrated into a chemical pulp mill with a production capacity of 230,000 ADt/yr of bleached kraft pulp.

In both cases, the sMCC and iMCC process equipment is similar. The raw material for iMCC is never dried kraft pulp of 30% consistency. Hydrolyzate from hydrolysis leads to a chemical pulp mill *via* an evaporation plant to a recovery boiler to produce energy from dissolved carbohydrates. Electricity and heat are supplied from a chemical pulp mill. Fresh water is used for the washing stage and used H₂SO₄ is imported to the plant.

Economic Analysis

The economic analysis is based on the cost-benefit analysis (CBA), where all investment and operational costs are itemized and the net benefit defined. The CBA is defined by the return on investment (ROI) and added value on purchased pulp.

The price of purchased pulp in the case of the iMCC is lower than in the case of the sMCC because the never-dried pulp is used and the drying costs of pulp are saved. In the economic calculations, the selling price of MCC (1,600 Euros/ADt) is lower than the existing market prices (4,000 to 10,000 Euros/ADt). Due to the moderate end-product price, it is assumed that a new application will be developed for the various fields of this traditional industry (*e.g.*, plastic and paper making). By using developed process concepts it is projected to attain a 5% share of the existing MCC markets. Moreover, it is possible to produce the new MCC grades with a high lignin content (if raw material is chemical pulp after digestion) for new application markets, such as animal feed additives (Dahl *et al.* 2013).

For the sMCC, power is provided by a public electricity network, and natural gas is imported to the mill site to generate steam for process purposes. This causes higher energy prices for the sMCC compared to the iMCC, where integration into the energy self-sufficient chemical pulp mill gives a reduction in energy prices.

An MCC production plant works in a five-shift system like the typical chemical pulp plants in Nordic countries; therefore, 25 operators are needed. In the integration case, some benefits are gained and the operator number is lower. Operator costs are based on the normal industrial salary standard in Finland (Elinkeinoelämän Keskusliitto 2012).

The difference in capital expenditure between the stand-alone and integrated plants lies in an auxiliary power boiler in the sMCC to generate medium pressure steam (14 to 17 bars). The specified boiler price includes feed water treatment, heavy oil heating, and steam distribution.

RESULTS AND DISCUSSION

Technology

The mass, water, and fuel calculations for the sMCC and iMCC are presented in Table 2. Differences in water amounts come from the difference in the raw material input streams between the two plants. The sMCC case uses pulp bales (90% dry consistency), and the iMCC case uses an undried pulp stream from a chemical pulp mill. Natural gas is used only with sMCC. The amount of dissolved carbohydrate is based on the hydrolysis yield. The power demand of the iMCC is 20 kWh/BDt lower than the sMCC because the shredding unit is not needed. Steam is used in the hydrolysis reactor and for drying.

Table 2. Mass, Water, and Fuel Calculations for sMCC and iMCC Cases

	Unit	sMCC case	iMCC case
Mass and water:			
Pulp needed, $C_{Pn} = C_{Mp} / C_{My}$	BDt/yr	33333	33333
Pulp water, $C_{Pw} = C_{Pn} / C_{Cons} - C_{Pn}$	t/yr	3704	77098
H ₂ SO ₄ amount, $C_{Aa} = C_{Pn} \times C_{A\%}$	t/yr	500	500
Dilution water, $C_{Dwa} = C_{Pn} / C_{Hyd} - C_{Pn} - C_{Pw} - C_{Aw}$	t/yr	73394	0
Water to mill, $C_{Wm} = C_{Dwa} + C_{Wwa}$	t/yr	88394	15000
MCC water, $C_{Mw} = C_{Mp} / C_{Dr} - C_{Mp}$	t/yr	3333	3333
Vapour out, $C_{Vo} = C_{Mp} / C_{Dw} - C_{Mp} / C_{Dr}$	t/yr	26667	26667
Filtrate amount, $C_{Fa} = C_{Pw} + C_{Aw} + C_{Wm} - C_{Mw} - C_{Vo}$	t/yr	62778	62778
Dissolved Carbohydrates, $C_{Dc} = C_{Pn} - C_{Mp}$	t/yr	3333	3333
Fuel:			
Power demand, C_{Ps}	kWh/BDt	300	280
Heat demand, C_{Hs}	GJ/BDt	5.0	4.3
Natural gas heat value, C_{Ng}	GJ/BDt	50.0*	
Efficiency factor, C_{Ef}		0.9	
Natural gas, $C_{Ng} = C_{Mp} \times C_{Hs} / C_{Ng} / C_{Ef}$	t/yr	3333	

*(Gasum 2014)

The heat demand for both processes is the same, but the iMCC benefits from a heat level of 0.7 GJ/BDt when the hydrolyzate is evaporated and then burned in the recovery boiler (Table 3).

Table 3. Heat Demand Saving Calculations in the iMCC Case

	Unit	iMCC case
Hydrolyzate evaporation:		
Evaporated to dry matter, C_{Edm}	%	80
Evaporation plant heat consumption, C_{7-s}	GJ/t _{H₂O}	0.4*
Evaporated water, $C_{Ew} = C_{Fa} - C_{H} / C_{Edm} - C_{Dc}$	t/yr	61944
Heat demand, $C_{Ewhd} = C_{Ew} \times C_{7-s} / C_{Mp}$	GJ/t	0.8
Recovery boiler:		
Heat Recovery in Recovery Boiler, C_{Hr}	%	80
Carbohydrate heat value, C_{Hhv}	GJ/t	17.6**
Produced heat from carbohydrates, $C_{Phc} = C_{Dc} \times C_{Hhv} \times C_{Hr} / C_{Mp}$	GJ/t	1.6
Net heat:		
Produced net heat, $C_{Pnh} = C_{Phc} - C_{Ewhd}$	GJ/t	0.7
Heat demand of iMCC case, $C_{Hs} = C_{Hs} (sMCC) - C_{Pnh}$	GJ/t	4.3

*7-stage evaporation (Gullichsen and Fogelholm 1999b)

**(Gullichsen 1968)

The flow charts of the sMCC and iMCC with calculated balances are shown in Figs. 3 and 4.

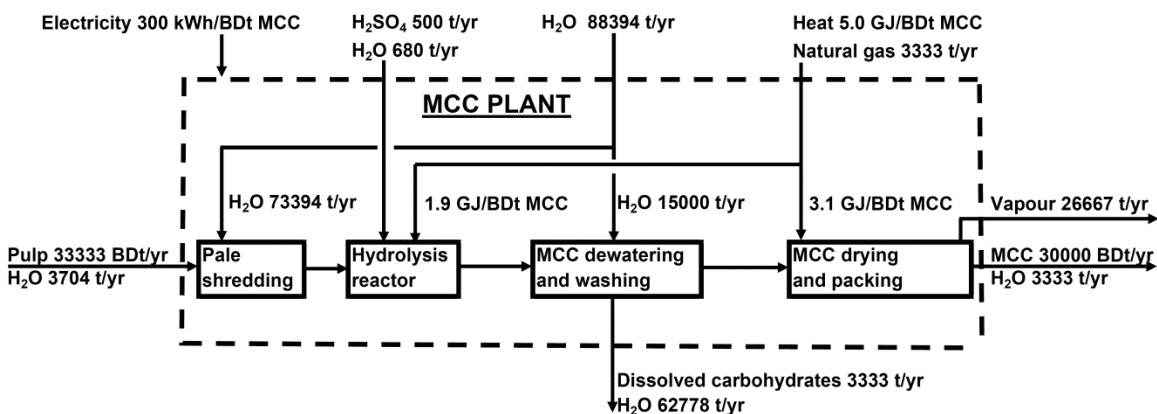


Fig. 3. Mass and energy balance of the sMCC case

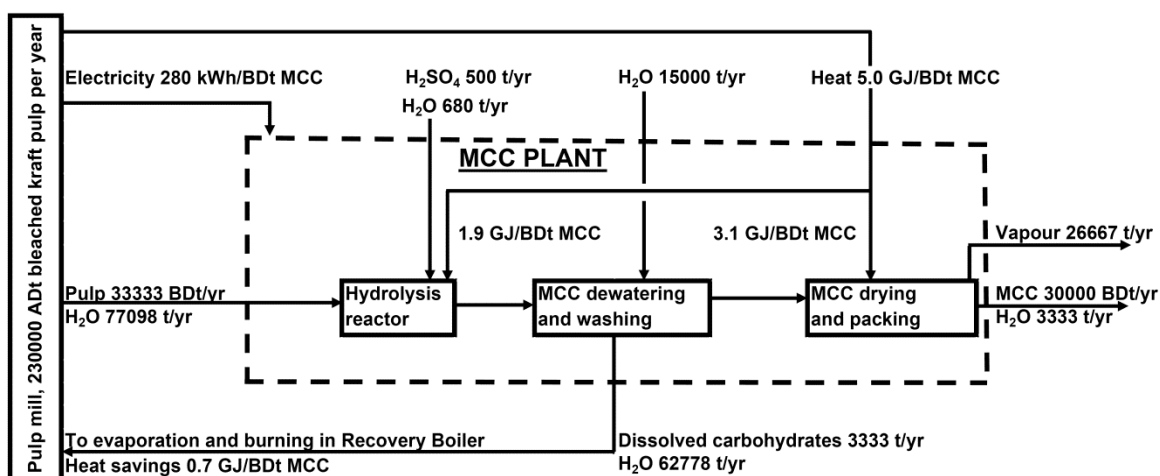


Fig. 4. Mass and energy balance of the iMCC case

In the integrated option, the hydrolyzate is led to an existing chemical pulp mill, where it is evaporated with black liquor before energy production in the recovery boiler. Hydrolysis acid dosage of 1.5% corresponds to 5.0 kgS/ADt of chemical pulp and 5.6 kgS/ton of MCC when the hydrolysis yield is 90%. A low dosage of acid in MCC manufacturing allows for cross-recovery with a chemical pulp mill, where the sulfur losses are typically 1.5 to 3.0 kgS/ADt (Gullichsen and Fogelholm 1999b). The Nordic softwood pulp mill constitutes a tall oil plant. In these pulp mills, tall oil yields are 0.04 to 0.06 $t_{\text{tall oil}}/\text{ADt}$ of chemical pulp, and a tall oil plant typically consumes 100 to 300 $\text{kgH}_2\text{SO}_4/t_{\text{tall oil}}$ (Gullichsen and Fogelholm 1999b). The sulfur amount generated in a tall oil plant is calculated in Eq. 1:

$$200 \frac{\text{kgH}_2\text{SO}_4}{t_{\text{tall oil}}} \times 0.04 \frac{t_{\text{tall oil}}}{\text{ADt}} \times \frac{32 \frac{\text{g}}{\text{mol}}}{98 \frac{\text{g}}{\text{mol}}} = 2.6 \frac{\text{kgS}}{\text{ADt}} \quad (1)$$

where 200 $\text{kgH}_2\text{SO}_4/t_{\text{tall oil}}$ is the typical acid consumption value of tall oil plant, 0.04 $t_{\text{tall oil}}/\text{ADt}$ is typical tall oil yield, 32 g/mol is molar mass of sulfur, and 98 g/mol is molar mass of H_2SO_4 .

There is a sulfur balance between sulfur feeds and sulfur losses in the recovery cycle of a pulp mill. This can be expressed according to Eq. 2,

$$S_{Feed} = S_{Losses} \quad (2)$$

where S_{Feed} is sulfur intake into the pulp mill and S_{Losses} are sulfur losses from the pulp mill.

The S_{Feed} consists of the sulfur amount from the tall oil plant and the sulfur amount from the MCC plant, while the S_{Losses} typically consist of chemical pulp mill sulfur losses.

The sulfur balance can also be expressed by Eq. 3,

$$S_{TOP} \times P_1 + S_{MCC} \times P_2 = S_{Losses} \times P_2 \quad (3)$$

where S_{TOP} is the sulfur amount from the tall oil plant, S_{MCC} is the sulfur amount from the MCC plant, P_1 is the production of a chemical pulp mill, and P_2 is the production of an MCC mill. Equation 3 can also be expressed by Eq. 4:

$$P_2 = \frac{S_{Losses} - S_{TOP}}{S_{MCC} \times P_1} \quad (4)$$

The MCC with a certain maximum capacity can be integrated into a chemical pulp mill and a capacity can be calculated by Eq. 5,

$$\frac{3.0 \frac{kgS}{ADt} - 2.6 \frac{kgS}{ADt}}{5.6 \frac{kgS}{t_{MCC}}} \times 230\,000 \frac{ADt}{yr} = 16429 \frac{t_{MCC}}{yr} \quad (5)$$

where 3.0 kgS/ADt is typical sulfur loss of pulp mill, 2.6 kgS/ADt is calculated (Eq. 1) sulfur amount which tall oil plant generates, 5.6 kgS/t_{MCC} is sulfur amount which is needed to MCC production, and 230,000 ADt/yr is chemical pulp mill annual production to where MCC process is integrated.

This cross-recovery, with a MCC plant capacity of 16,429 t_{MCC}/yr, can be implemented without adjusting the sulfur balance of the chemical pulp mill. Because the products of hardwood mills (*e.g.*, eucalyptus) yield no extractives such as tall oil, a larger cross recovery rate can be applied and a larger MCC plant can be implemented.

Some softwood mills use the preacidulation process with CO₂ found in a tall oil plant. This approach lowers the amount of needed H₂SO₄ in tall oil plant, hence a bigger cross-recovery rate can be applied; *e.g.*, the charge 100 kgH₂SO₄/t_{tall oil} is valid when the preacidulation with CO₂ is adapted in the tall oil refining process. In this case, an MCC plant with higher capacity can be implemented without adjusting a pulp mill sulfur balance, and can be calculated in Eqs. 6 and 7,

$$100 \frac{kgH_2SO_4}{t_{tall\ oil}} \times 0.04 \frac{t_{tall\ oil}}{ADt} \times \frac{32 \frac{g}{mol}}{98 \frac{g}{mol}} = 1.3 \frac{kgS}{ADt} \quad (6)$$

where 100 kgH₂SO₄/t_{tall oil} is acid consumption value of pulp mill tall oil plant which uses CO₂ preacidulation process, 0.04 t_{tall oil}/ADt is typical tall oil yield, 32 g/mol is molar mass of sulfur, and 98 g/mol is molar mass of H₂SO₄,

$$\frac{3.0 \frac{\text{kgS}}{\text{ADt}} - 1.3 \frac{\text{kgS}}{\text{ADt}}}{5.6 \frac{\text{kgS}}{\text{t}_{\text{MCC}}}} \times 230000 \frac{\text{ADt}}{\text{yr}} = 69821 \frac{\text{t}_{\text{MCC}}}{\text{yr}} \quad (7)$$

where 3.0 kgS/ADt is typical sulfur loss of pulp mill, 1.3 kgS/ADt is calculated (Eq. 6) sulfur amount which tall oil plant generates when CO₂ preacidulation process is used, 5.6 kgS/t_{MCC} is sulfur amount which is needed to MCC production, and 230,000 ADt/yr is pulp mill annual production to where MCC process is integrated.

Economic Analysis

The default investment and operational costs used in the calculation are listed in Table 4.

Table 4. Defaults Used for the Investment and Operational Costs Calculation

	Unit	sMCC case	iMCC case
Price of purchased pulp, C _{PPP}	euros/ADt	630	605
Heat unit cost, C _{Huc}	euros/MWh	50.0*	30.0
Power unit cost, C _{Puc}	euros/MWh	90.0**	30.0
Operator unit cost, C _{Ouc}	euros/operator/yr	60000	60000
Number of operators, C _{No}		25.0	20.0
MCC mill cost, C _{Mmc}	mill. euros	25.0	25.0
Power plant cost, C _{Ppc}	mill. euros	1.5	0.0
Maintenance costs constant, C _{Mcc}	% of project costs	4.0	4.0
Fixed cost (without depreciation) constant, C _{Fcc}	% of project costs	15.0	15.0
Capital cost (annuitet), constant C _{Ccc}	% of project costs	13.0	13.0
Selling price, C _{Sp}	euros /ADt	1600	1600
H ₂ SO ₄ unit price, C _{Ap}	euros/ton	40.0	40.0

* (Tilastokeskus 2013a)

** (Tilastokeskus 2013b; Tulli 2013)

Because pulp is not dried in the iMCC case, savings gained are calculated in Eq. 8,

$$2500 \frac{\text{MJ}}{\text{ADt}} \times \frac{\text{h}}{3600\text{s}} \times 30 \frac{\text{€}}{\text{MWh}} + 0.15 \frac{\text{MWh}}{\text{ADt}} \times 30 \frac{\text{€}}{\text{MWh}} = 25 \frac{\text{€}}{\text{ADt}} \quad (8)$$

where 2500 MJ/ADt (Gullichsen and Fogelholm 1999b) is the heat consumption of a drying machine, 0.15 MWh/ADt (Gullichsen and Fogelholm, 1999b) is the power consumption of a drying machine, and €/MWh values are chemical pulp mill typical internal costs of heat and power (Table 4).

In the case of iMCC, the chemical pulp mill generates electrical power with its own back pressure turbo-generator set. High pressure steam to the turbine is taken from a recovery boiler and a power boiler. Medium- and low-pressure steams from the turbine are further distributed into the MCC process. This implies that steam in the processes can be credited with power generation and the steam or heat price is lower compared to the case of sMCC, where power is bought from a public electricity network and heat is created with natural gas in a biofuel boiler.

The calculated total project costs and operational costs of the sMCC case and the iMCC case are shown in Table 5.

Table 5. Operational and Total Cost of the sMCC and the iMCC Case

	Unit	sMCC case	iMCC case
Pulp cost, $C_{Pc} = C_{Pn} / 0.9 \times C_{Ppp} / 1000000$	mill. euros/yr	23.3	22.4
Heat cost, $C_{Hc} = C_{Hs} / 3.6 \times C_{Huc} * C_{Mp} / 1000000$	mill. euros/yr	2.1	1.1
Power cost, $C_{Poc} = C_{Ps} / 1000 \times C_{Mp} \times C_{Puc} / 1000000$	mill. euros/yr	0.8	0.3
Operator costs, $C_{Oc} = C_{Ouc} \times C_{No} / 1000000$	mill. euros/yr	1.5	1.2
Maintenance costs, $C_{Mc} = C_{Mcc} \times (C_{Mmc} + C_{Ppc})$	mill. euros/yr	1.1	1.0
Fixed cost (without depreciation), $C_{Fc} = C_{Fcc} \times (C_{Mmc} + C_{Ppc})$	mill. euros/yr	4.0	3.8
Capital cost (annuitet), $C_{Cc} = C_{Ccc} \times (C_{Mmc} + C_{Ppc})$	mill. euros/yr	3.4	3.3
H ₂ SO ₄ cost, $C_{Ac} = C_{Aa} \times C_{Ap} / 1000000$	mill. euros/yr	0.02	0.02
Total operation cost, $C_{Toc} = C_{Pc} + C_{Hc} + C_{Poc} + C_{Oc} + C_{Mc} + C_{Fc} + C_{Cc} + C_{Ac}$	mill. euros/yr	36.2	33.0
Total project costs, $C_{Tpc} = C_{Mmc} + C_{Ppc}$	mill. euros	26.5	25.0

The total project costs include the costs of the land plot, building, civil work, machinery (with tanks and pipes), utilities, electrical equipment, process control, consulting services, and erection and start-up of all machinery. Typically, a contingency of 20% of the investment are considered in the estimates. The main machinery of both plant options (stand-alone and integrated) are of the same size and capital expenditure. The total project cost estimates are derived on the basis of the earlier pre-engineering MCC projects.

Cost-benefit and Sensitivity Analyses

The operational cost and total project expenditure information used to produce the cost-benefit analysis is shown in Table 6.

Table 6. Cost-Benefit Analysis for the sMCC and iMCC Cases

	Unit	sMCC case	iMCC case
Selling income, $C_{Si} = C_{Mp} \times C_{Sp} / 1000000 / 0,9$	mill. euros/yr	53.3	53.3
Depreciation (20 % of invest.), $C_{D,20\%} = 0.2 \times C_{Tpc}$	mill. euros/first year	5.3	5.0
Net profit before taxes, $C_{Npbt} = C_{Si} - C_{Toc}$	mill. euros/first year	17.1	20.4
Taxes (20 %, 2014 ahead), $C_{T,20\%} = (C_{Npbt} - C_{D,20\%}) \times 0.2$	mill. euros/first year	2.4	3.1
Net benefit after taxes, depreciation of 20 % considered, $C_{Npat} = C_{Npbt} - C_{T,20\%}$	mill. euros/first year	14.7	17.3
ROI, $C_{ROI} = C_{Npat} / C_{Tpc} \times 100$	%	55.6	69.2
Added value on purchased pulp, $C_{Avpp} = C_{Npat} / C_{Pc} \times 100$	%	63.2	77.2

As seen in Table 6, the ROI and added value on purchased pulp seems to be viable and feasible for both examined options. The iMCC case gives 13.6% units of higher ROI

values compared to the stand-alone alternative. The corresponding benefit to the added value of purchased pulp is 14.0%.

Sensitivity analysis for ROI and added value on purchased pulp is based on changes in the price of raw material, product, energy, and chemicals from -30% to +30% calculated from default values (Tables 1 through 6). The sensitivity analysis of ROI and the added value where the costs of raw material, product unit, power, and chemicals are taken into account are presented in Figs. 5a, 5b, 6a, and 6b.

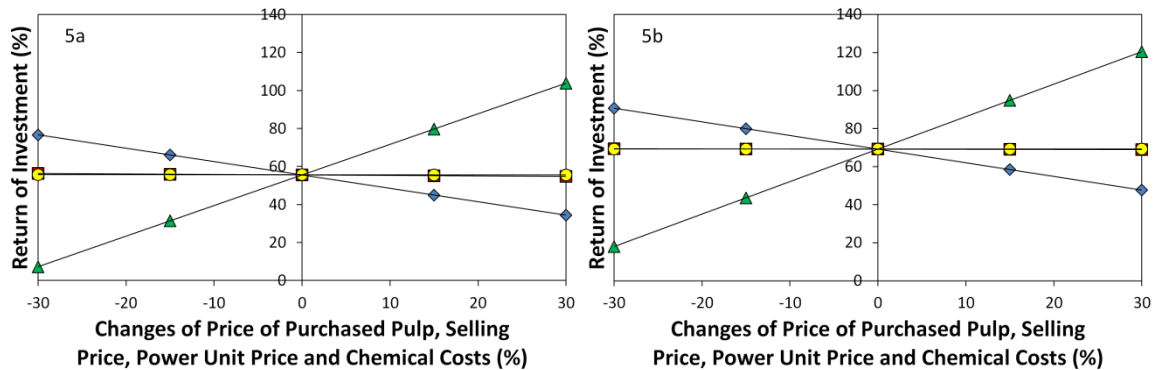


Fig. 5. ROI as a function of changes in (a) sMCC case and (b) iMCC case. Price of purchased pulp (\blacklozenge), product selling price (\blacktriangle), power unit price (\blacksquare), and chemical costs (\blacklozenge). Default values (x-axis value 0%) are taken from Tables 1 through 6.

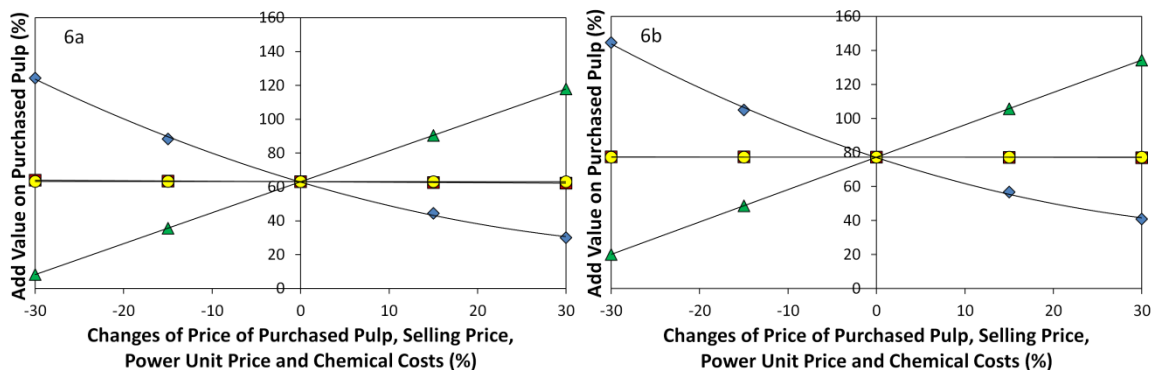


Fig. 6. Added value on purchased pulp as a function of changes in (a) sMCC case and (b) iMCC case. Price of purchased pulp (\blacklozenge), product selling price (\blacktriangle), power unit price (\blacksquare), and chemical costs (\blacklozenge). Default values (x-axis value 0%) are taken from Tables 1 through 6.

The raw material and product prices have an essential effect on the investment economy (the ROI and the added value of purchased pulp), while the effect of the price of energy or chemicals were insignificant within the utilized range of -30% to +30%. Normally, when the ROI is 15% or more, the company's operations are highly profitable. Using this estimation, the lower values of ROI can be achieved only when the selling price of the product decreases more than 25.3%, which equates to 1200 €/ADt in the stand-alone scenario, and 31.7% which equates to 1092 €/BDt in the integrated scenario. However, such low prices for MCC have never been seen in this market.

CONCLUSIONS

1. Both process options, the sMCC and the iMCC, show strong profitability when return of investment and added value are used as economic indicators.
2. The iMCC case provides the better economical asset measured with ROI and added value on purchased pulp. In addition to the operational savings (or net profit before taxes), when the MCC plant is integrated and implemented into the chemical pulp mill the annual savings are about 19% (3.3 million euros) relative to the non-integrated option.
3. Integration also allows minor economic risk of investment, since production in the MCC plant can be halted (*e.g.*, routine maintenance) and chemical pulp still produced in a conventional manner.

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REFERENCES CITED

- Adel, A. M., El-Wahab, Z. H. A., Ibrahim, A. A., and Al-Shemy, M. T. (2010). "Characterization of microcrystalline cellulose prepared from lignocellulosic materials. Part I. Acid catalyzed hydrolysis," *Bioresource Technology* 101 (12), 4446-4455.
- Battista, O. A., Hill, D., and Smith, P. A. (1961). "Level-off D.P cellulose products," *U.S. Patent 2,978,446*.
- Battista, O. A., and Smith, P. A. (1962). "Microcrystalline cellulose - The oldest polymer finds new industrial uses," *Ind. Eng. Chem.* 54(9), 20-29.
- Bergfeld, M. J., and Seifert, J. (1996). "Process for the preparation of level-off DP cellulose," *US Patent 5,543,511 A*.
- Biermann, C. J. (1993). "Pulping fundamentals," in: *Essentials of Pulping and Papermaking*, Academic Press, San Diego, USA.
- Braunstein, E. L., Dostie, R. L., Germano, K. H., Lamb, S. C., Penet, C. S., and Richards, P. B. (1994). "Crystalline cellulose production," *US Patent 5,346,589 A*.
- Brännvall, E. (2007). "Pulping technology," in: *Pulping Chemistry and Technology*, M. Ek, G. Gellerstedt, and G. Henriksson (eds.), Fiber and Polymer Technology, KTH, Sweden, pp. 121-148.
- Brinkman, I., and Schaible, D. (2003). "Process for producing microcrystalline cellulose," *US Patent application 2003/0089465 A1*.
- Chornet, E., and Jollez, P. (1999). "Process for preparing a high purity chemical-free microcrystalline cellulose from a chemically produced cellulose," *WO 1999/060027 A1, Patent application PCT/CA1998/000479*.

- Chornet, E., Cloutier, S., and Jollez, P. (2006). "Process for producing low DP microcrystalline cellulose," *US Patent 6,986,828 B2*.
- Ciechanska, D., Urbanowski, A., Wesolowska, E., Jeropulos, M., Wawro, D., Kucharska, M., and Kazimierczak, J. (2010). "Market study on main polysaccharides - Final report," *European Polysaccharide Network of Excellence (EPNOE, www.epnoe.eu), Institute of Biopolymers and Chemical Fibres. ul. Skłodowskiej-Curie 19/27, 90-570 Lodz, Poland*.
- Cruz, M. M. (1983). "Readily hydratable cellulose and preparation thereof," *US Patent 4,391,973 A*.
- Dahl, O., Parviainen, K., and Vanhatalo, K. (2013). "Use of pure cellulose in increasing the energy content of fodder," *WO 2013/132159 A1, Patent application PCT/FI2013/050250*.
- Dahl, O., Vanhatalo, K., Parviainen, K., and Svedman, M. (2011a). "A novel method to produce microcellulose," *WO 2011/154601 A1, Patent application PCT/FI2011/050527*.
- Dahl, O., Vanhatalo, K., and Parviainen, K. (2011b). "A novel method to produce microcellulose," *WO 2011/154600 A2, Patent application PCT/FI2011/050526*.
- De Long, E. A. (1989). "Method of producing level off DP microcrystalline cellulose and glucose from lignocellulosic material," *EP 0170530 B1*.
- Dobashi, S., Ohara, K., and Uchida, H. (1992). "Method for preparing powdery crystalline cellulose," *US Patent 5,175,275 A*.
- El-Sakhawy, M., and Hassan, M. L. (2007). "Physical and mechanical properties of microcrystalline cellulose prepared from agricultural residues," *Carbohydrate Polymers* 67(1), 1-10.
- Elanthikkal, S., Gopalakrishnanpanicker, U., Varghese, S., and Guthrie, J. T. (2010). "Cellulose microfibrils produced from banana plant wastes: Isolation and characterization," *Carbohydrate Polymers* 80(3), 852-859.
- Elinkeinoelämän keskusliitto. (2012). "Palkkatilasto 4.neljännekseltä 2012," http://www.ek.fi/ek/fi/tutkimukset_julkaisut/2013/4_huhti/Tuntipalkkatilasto-4_neljannes-2012-net.pdf (accessed Jan 15, 2014).
- Food and Agriculture Organization of the United Nations. (1996). "Microcrystalline cellulose," <http://www.fao.org/docrep/W6355E/w6355e01.htm> (accessed Mar 13, 2013).
- Food and Agriculture Organization of the United Nations (2011). "Pulp and paper capacities 2010-2015," <http://www.fao.org/docrep/014/i2285t/i2285t00.pdf> (accessed Sep 17, 2013).
- Frangioni, G., and Frangioni, A. P. (2010). "Method for preparing microcrystalline cellulose," *Patent application PCT/IB2010/001001*.
- Frangioni, G., and Frangioni, A. P. (2012). "Method for preparing microcrystalline cellulose," *US Patent application 2012/0135505 A1*.
- Gasum. (2014). "Natural gas-A clean-burning natural energy gas," <http://www.gasum.com/Facts-about-gas-/Natural-gas/> (accessed Feb 4, 2014).
- Gospodinov, N. R., Toshkov, T. S., and Vidimski, E. P. (1976). "Method of producing microcrystalline cellulose," *US Patent 3,954,727 A*.
- Gullichsen, J. (1968). "Heat values of pulping spent liquors," *Proceedings of IUPAC EUCEPA Symposium: Recovery of Pulping Chemicals*, Helsinki, Finland, pp. 214.
- Gullichsen, J., and Fogelholm, C.-J. (eds.) (1999a). *Chemical Pulping, Papermaking Science and Technology ser., 6A*, Fapet Oy, Helsinki.

- Gullichsen, J., and Fogelholm, C.-J. (eds.) (1999b). *Chemical Pulping, Papermaking Science and Technology ser., 6B*, Fapet Oy, Helsinki.
- Guo, J. X., Mattheson, J., and Shaver, L. (2002). "Microcrystalline cellulose manufacture," *WO 02/057540 A1, Patent application PCT/US2002/000103*.
- Haafiz, M., Eichhorn, S. J., Hassan, A., and Jawaid, M. (2013). "Isolation and characterization of microcrystalline cellulose from oil palm biomass residue," *Carbohydrate Polymers* 93(2), 628-634.
- Ha, E. Y. W., and Landi, C. D. (1998). "Method for producing microcrystalline cellulose," *US Patent 5,769,934 A*.
- Ilindra, A., and Dhake, D. J. (2008). "Microcrystalline cellulose from bagasse and rice straw," *Indian Journal of Chemical Technology* 15(5), 497-499.
- Ioelovich, M., and Leykin, A. (2005). "Method of producing microcrystalline cellulose-containing compositions," *US Patent application 2005/0239744 A1*.
- James, E. S., Persinger, W. H., Luo, M., and Wester, B. (2003). "Sawdust alkaline pulp having low average degree of polymerization values and method of producing the same," *US Patent 6,605,350 B1*.
- Kalita, R. D., Nath, Y., Ochubiojo, M. E., and Buragohain, A. K. (2013). "Extraction and characterization of microcrystalline cellulose from fodder grass; *Setaria glauca* (L) P. Beauv, and its potential as a drug delivery vehicle for isoniazid, a first line antituberculosis drug," *Colloids and Surfaces B: Biointerfaces* 108, 85-89.
- Kazakova, E. G., and Demin, V. A. (2009). "A new procedure for preparing microcrystalline cellulose," *Russian Journal of Applied Chemistry* 82(3), 496-499.
- Kopesky, R., Ruskay, T. A., and Tsai, A. G. (2004). "Production of microcrystalline cellulose," *WO 2004/011501 A1, Patent application PCT/US2003/022988*.
- Luo, M., and Neogi, A. N. (2006). "Microcrystalline cellulose and method for making," *Patent application EP 20060251713*.
- Milford, A. H., Biby, G., and Miladinov, V. (2001). "Production of microcrystalline cellulose by reactive extrusion," *US Patent 6,228,213 B1*.
- Nada, A-A. M. A., El-Kady, M. Y., El-Sayed, E. S. A., and Amine, F. M. (2009). "Preparation and characterization of microcrystalline cellulose (MCC)," *BioResources* 4(4), 1359-1971.
- Nguyen, X. T. (2006). "Process for preparing microcrystalline cellulose," *US Patent 7,005,514 B2*.
- Nguyen, X. T., and Tan, Z. (2006). "Surface treatment with texturized microcrystalline cellulose microfibrils for improved paper and paper board," *US Patent 7,037,405 B2*.
- Perry, R. H., Green, D.W., and Maloney, J. O. (eds) (1984). *Perry's Chemical Engineers' Handbook*, McGraw Hill, New York, USA.
- Schaible, D., and Sherwood, B. (2005). "Treatment of pulp to produce microcrystalline cellulose," *US Patent application 2005/0145351 A1*.
- Sixta, H., Iakovlev, M., Testova, L., Roselli, A., Hummel, M., Borrega, M., van Heiningen, A., Froschauer, C., and Schottenberger, H. (2013). "Novel concepts of dissolving pulp production," *Cellulose* 20(4), 1547-1561.
- Tilastokeskus. (2013a). "Sähkön hinta kuluttajatyypeittäin," http://www.stat.fi/til/ehi/2013/03/ehi_2013_03_2013-12-18_kuv_005_fi.html (accessed Jan 15, 2014).
- Tilastokeskus. (2013b). "Energian hintoja lämmöntuotannossa syyskuussa 2013," http://www.stat.fi/til/ehi/2013/03/ehi_2013_03_2013-12-18_tau_002_fi.html (accessed Jan 29, 2014).

- Townsley, P. M. (1988). "Method for producing cellulosic fibers and microcrystalline cellulose," *US Patent 4745058 A*.
- Trache, D., Donnot, A., Khimeche, K., Benelmir, R., and Brosse, N. (2014). "Physico-chemical properties and thermal stability of microcrystalline cellulose isolated from Alfa fibres," *Carbohydrate Polymers* 104, 223-230.
- Trusovs, S. (2001). "Microcrystalline cellulose," *US Patent 6,392,034 B1*.
- Tuason, D. C., Krawczyk, G. R., and Buliga G. (2009). "Microcrystalline cellulose," in: *Food Stabilisers, Thickeners and Gelling Agents*, A. Imeson (ed.), Wiley-Blackwell, Chichester, United Kingdom.
- Tulli. (2013). "Energiaverotus," http://www.tulli.fi/fi/suomen_tulli/julkaisut_ja_esitteet/asiakasohjeet/valmisteverotus/tiedostot/021.pdf (accessed Jan 15, 2014).
- Vanhatalo, K., and Dahl, O. (2014). "Effect of mild acid hydrolysis parameters on properties of microcrystalline cellulose," *BioResources* 9(3), 4729-4740.
- Woodruff, K. L. (1986). "Process and materials handling equipment: Rotary shear shredders, design and operation," in: *The Solid Waste Handbook- A Practical Guide*, W. D. Robinson (ed), John Wiley & Sons, New York, USA.
- Yaginuma, Y., Nagatomo, S., and Miyamoto, H. (1996). "Excipient having high compactability and process for preparing same," *US Patent 5,574,150*.
- Zabriskie, D. W. (1984). "Enzymatic preparation of particulate cellulose for tablet making," *US Patent 4,427,778 A*.

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