Cost–Benefit Analysis of Medium-Density Fiberboard Production by Adding Fiber from Recycled Medium-Density Fiberboard

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Abstract

Waste medium-density fiberboard (MDF) is mostly disposed of in landfills and left for incineration. The consequences of filling MDF waste to the landfill include undesirable associated costs and environmental problems caused by incineration. In this study, a prediction method is used for calculating the thermal energy required to recycle MDF fibers. The recycling method consists of a high-temperature treatment in a preheater at an operating temperature of 100°C, which melts the resin and separates the fibers. The cost reduction and energy savings of virgin wood material are calculated for MDF that has been manufactured by replacing 10 and 20 percent of the wood fiber with recycled fiber. Results show that the benefits of MDF production using 10 percent recycled fiber result in a 10 percent reduction in virgin wood material costs and an energy savings of 3.9 percent. Using 20 percent recycled fiber results in an estimated 20 percent reduction in the cost of virgin wood material and an energy savings of 7.8 percent for MDF production. The predicted amounts of thermal energy required to produce MDF are consistent with those of previous studies.

Medium-density fiberboard (MDF) is a highly demanded product in the furniture industry because of its strength and ease to process. It is a composite panel manufactured by pressing wood fiber with adhesives at high pressure and high temperature. Total disposal of MDF material in the United Kingdom in 2007 is shown in Table 1. The cost for incineration and landfilling were ₤679,000 and ₤4,390,000, respectively, in 2007, whereas the charges for landfilling has increased twice on the basis of the current landfill tax (Beele 2009). In addition to CO_2 emissions, CH_4 and NO, which result from incineration, can cause environmental problems such as global warming. All of these environmental problems and disposal-cost issues of MDF can be solved by recycling the material, which is an alternative and environmentally friendly method. Numerous studies have been conducted on recycling MDF. Most of the studies used a process of shredding and heating the MDF waste at a temperature of 90°C to 100°C to melt the resin.

Lubis et al. (2018) focused their study on the removal of urea-formaldehyde resin to make reusable MDF. For this, they conducted various experiments by changing temperature, treatment time, and different aqueous solutions. They concluded that the optimum condition for removing the resin is by hydrolysis with oxalic acid at a temperature of 80°C for 2 hours, and their subsequent work involved hydrolysis with water. Several researchers used a hydrothermal approach for recycling the wood waste (Lykidis and Grigoriou 2008, Roffael and Huster 2012). Athanassiadou et al. (2005) presented a novel extrusion process for recycling the MDF boards with waste particled. The obtained fibers were suitable for MDF production. Under the high shear in a twin-screw extruder, the recycled material is exposed for thermohydrolysis, which changes the morphological structure of the fibers. Because of the limitation of the MDF fibers, Athanassiadou et al. (2005) used only 15 percent of recycled material, which gave similar mechanical properties compared with MDF made from new material.

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This paper was accepted for publication in November 2017. Article no. 17-00081.

Forest Prod. J. 68(4):414–418.
doi:10.13073/FPJ-D-17-00081

Table 1.—Waste and disposal for medium-density fiberboard (MDF; t) manufacture and use in the furniture industry in 2007 in the United Kingdom.

	MDF manufacture	Furniture manufacture	Total
Incineration	0	36,720	36,720
Landfill	36,774	107,100	143,874
Used as fuel	94,562	9,180	103,742

Currently, the MDF production process (Chapman 2004) can be classified into different steps, which include chipping, preheating, drying, pressing, and forming. First the logs are fed into a chipper machine to create small wood chips. These chips are then washed with water and fed to a preheater with the help of a plug screw, which also prevents a backflow of wood chips. Thereafter the chips are heated with steam at 7 to 8 bar pressure and 170°C to 180°C temperature. Heating helps to separate fibers and weaken the bond between chips and fibers due to lignin. A refiner is used after heating to separate small pieces of fibers from chips. After collecting the refined fibers from the refiner they are dried. In a separated blow line, the resin is mixed with the fibers. The mixture of resin and fibers are again dried as necessary. In the end, fibers are pressed at high temperature and high pressure until they achieve the desired thickness. This study proposed that if some portion of recycled MDF in the manufacturing process is used it can save the disposal cost and reduce the production cost. The objective of this paper is to analyze possible economic benefits when recycled fibers from waste MDF are used in MDF production as a substitute for virgin fiber.

The recycling cost of MDF is calculated by applying some constraints on the model. The method assumed for recycling the MDF is a heat-treatment method in a preheater with an operating temperature of 100°C, whereas other processes remain the same as that of a production line. The waste MDF material price is assumed to be zero. The annual production cost of MDF is calculated by modifying a model of thermal energy demand, and the results are validated with Li et al. (2007).

Calculation of Required Thermal Energy in MDF Production

According to Li et al. (2007), annual energy demand for MDF production is based on natural preheating and refining and is shown in Figure 1. From the figure it can be seen that approximately 40 percent of the whole energy is consumed by the preheating and refining process and the calculation accuracy is approximately –17 to +6 percent.

To calculate the energy demand for 120,000 m^3/yr of MDF production, only four operation units (preheating, refining, drying, mat forming) are considered because almost all of the thermal energy is used by these operations. Chipping and washing are not considered because they use very little thermal energy. For around 350 days in a year, the operational time of an MDF factory is around 22.5 h/day and wood supply is around 12,220 kg/h, which approximately produces 120,000 m^3/yr of MDF. For MDF natural virgin wood originates from pine and the resin used is urea-formaldehyde. The moisture content (MC) of the wood is defined as the ratio of water weight in the wood to dried wood weight and the specific heat for wet wood is defined as a function of MC = 4,184 (MC + 0.328) J/kg (Pang et al. 1995). For all other specific heat constants, average value in operating temperature range (100°C to 180°C) is used. Figure 2 shows a schematic process of washing and screw feeder.

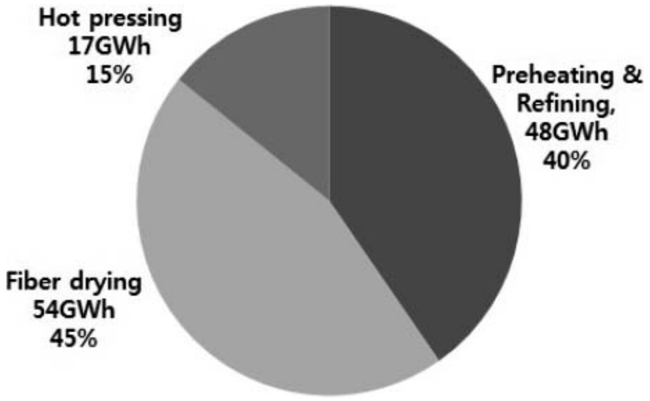


Figure 1.—Annual thermal energy demand by unit operation for production of 120,000 m^3/yr regular medium-density fiberboard using flue gas for fiber drying.

First the natural wood is chipped, and those chips are fed to the washing part of the process. In reality, the loss of wood occurs during washing; however, we assume that there is no loss of chips during analysis. After washing, the typical temperature of wood chips reached approximately 95°C. The energy balance for the wood chips in the washing process is defined by Equation 1 and initial MC is 150 percent (Pang et al. 1995).

$$Q_{\mathrm{wash}} = \frac{\dot{m}_{\mathrm{chip}} C_{\mathrm{p,chip}} (T_0 - T)}{1 - \mathrm{heatloss}} \tag{1}$$

where $\dot{m}_{\mathrm{chip}}$ is wood supply flow rate (kg/h) and C_{p} is specific heat.

After cleaning the wood chips, they are fed to a chip hopper where saturated steam is supplied at 0.4 MPa. The electrical energy required is around 2 kWh. By choosing the feed screw control volume, the energy balance equation is defined by Equation 2, from which required steam can be calculated. Fully saturated MC is 100 percent (Chan 2007).

$$\frac{\dot{m}_{\mathrm{chip}} C_{\mathrm{p,0}} (T_1 - T_0)}{1 - \mathrm{heatloss}} = \dot{m}_1 \left[C_{\mathrm{p,v}} (T_{\mathrm{steam\ 1}} - T_{\mathrm{steam\ 2}}) + \Delta H_{\mathrm{wv}} \right] + 3{,}600\alpha 1\, N_{\mathrm{scf}} \dot{m}_{\mathrm{chip}} \tag{2}$$

where $C_{\mathrm{p,v}}$ is the specific heat of steam (J/kgK), ΔH_{wv} is the specific heat of vaporization (J/kg), and N_{scf} is the electric

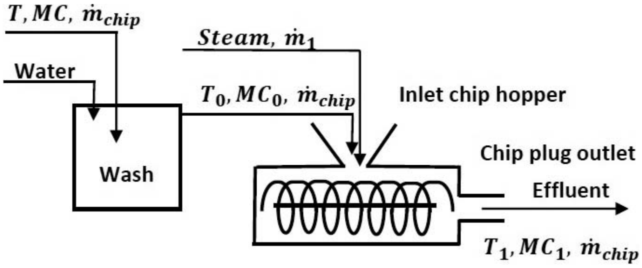


Figure 2.—Washing and screw-feeding process. See the text for definitions of abbreviations.

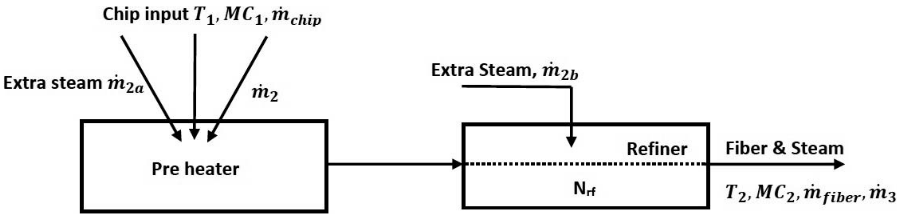


Figure 3.—Preheater and refiner process. See the text for definitions of abbreviations.

energy of the feed screw (kWh/t). Figure 3 illustrates the process of preheating and refining where chips are fed to a digester vessel.

During the preheating and refining process, it is assumed that all wood chips are changed to fibers and both have the same pressure and temperature as in Li et al. (2007). Steam from the refiner to the preheater is excluded in this process. Wood chip temperature T_2 was kept constant in preheating and refining. An additional assumption made in this study was that all of the supplied steam to the preheater should be absorbed into the wood chips and there is no loss of steam in the process. By using increased wood chip temperature, the required steam for preheating can be calculated by the energy balance, Equation 3. The actual steam requirement is about 30 percent ($\dot{m}_{2a}$) more than calculated.

$$\dot{m}_2 = \frac{\dot{m}_{\mathrm{chip}} C_{\mathrm{p},1}(T_2 - T_1)}{\Delta H_{\mathrm{wv}}(1 - \text{heat loss})} \tag{3}$$

By changing the electric energy of the refiner (185 kWh/t) to thermal energy, steam generated from the refiner is calculated by Equation 4.

$$\dot{m}_{\mathrm{g}} = \frac{0.001\alpha 2\, N_{\mathrm{rf}} \dot{m}_{\mathrm{chip}}}{\Delta H_{\mathrm{wv}}} \tag{4}$$

where $\dot{m}_{\mathrm{g}}$ is the generated steam flow rate at the refiner (kg/h) and N_{rf} is the electric energy of the refiner (kWh/t).

Steam out of the refiner and MC at the exit of the refiner (MC_2) should also be calculated. By assuming that wood chips absorb all steam supplied, steam out from the refiner can be calculated using Equation 5.

$$\dot{m}_3 = \dot{m}_a + \dot{m}_{2b}\,(\sim 400\,\mathrm{kg/h}) \tag{5}$$

MC_2 is calculated by the mass conservation of water in wood chips in Equation 6.

$$\mathrm{MC}_2 = \frac{\dot{m}_{\mathrm{chip}}\mathrm{MC}_1 + \dot{m}_2 + \dot{m}_{2a}}{\dot{m}_{\mathrm{fiber}}} \tag{6}$$

where $\dot{m}_{\mathrm{fiber}}$ is the fiber flow rate (kg/h).

Figure 4 shows complete process of blow line. No energy is required in the blow line, but the blow line should be considered for the resin addition and drying of fibers. At the blow-line inlet, temperature is increased and steam gets superheated, which evaporates the water from the fibers and injected resin solution from wood chips. The amount of evaporated vapors is calculated by the mass conservation of water in wood and resin solutions, Equation 7.

$$\dot{m}_{\mathrm{evap}} = \dot{m}_{\mathrm{w}} + \dot{m}_{\mathrm{fiber}}\,\mathrm{MC}_2 - \mathrm{MC}_3(\dot{m}_{\mathrm{fiber}} + \dot{m}_{\mathrm{r}}) \tag{7}$$

where $\dot{m}_{\mathrm{evap}}$ is the evaporated steam flow rate at blow line (kg/h), $\dot{m}_{\mathrm{w}}$ is the resin solution flow rate (kg/h), and $\dot{m}_{\mathrm{r}}$ is the resin flow rate (kg/h).

The steam mass flow rate during exit is equal to the sum of the steam mass flow rate at the inlet and the evaporated steam, as denoted by Equation 8.

$$\dot{m}_4 = \dot{m}_3 + \dot{m}_{\mathrm{evap}} \tag{8}$$

The pressure loss during exit is defined by Equation 9, using a friction factor of 0.025, a length (l) of 50 m, blow-line diameter (d) of 0.1 m, and a steam-fiber velocity (u) of 100 m/s. To calculate the temperature at the inlet, an empirical correlation is used as in Equation 10. The unit of pressure in Equation 10 is bar.

$$\Delta P = 0.025\,\frac{1}{d}\,\frac{u}{2}\,\frac{\dot{m}_3/3{,}600}{\pi d^2/4} \tag{9}$$

$$T_3 = 50\log_{10}(P_{\mathrm{out}}) + 3.48P_{\mathrm{out}} + 96.5 \tag{10}$$

From the conservation law of energy, the energy absorbed by the materials in the blow line is equal to the sum of latent thermal energy from the superheated steam and energy of materials at the exit. This energy balance is shown as Equation 11. Li et al. (2007) did not consider MC in the wood chips at inlet because the specific heat of the wood chips is changed to the specific heat of the fiber, 1,339.776 J/kgK (Perry et al. 1998), which is considered the energy of water. It is assumed that heat loss is negligible in this process and it is neglected. To solve the energy balance, another equation is needed because there are two unknowns, the evaporated vapor and MC upon departure t. For MC during exit, the mass conservation equation is defined as Equation 12.

By coupling Equations 11 and 12 and solving it simultaneously, the evaporated vapor in the blow line can be found. For the remaining process (drying and pressing), it is calculated as in Li et al. (2007). The thermal energy demand in MDF production is calculated in an Excel program as shown in Figure 5. The input values are the mass of supplied wood per hour, the mass ratio of wood to resin, and the operating temperature of the preheater.

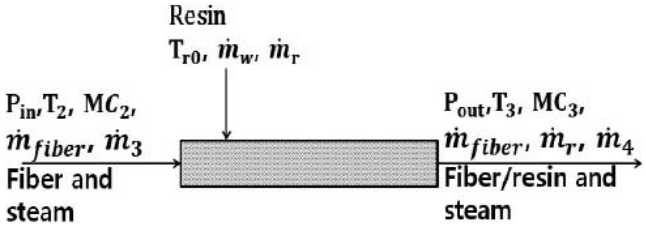
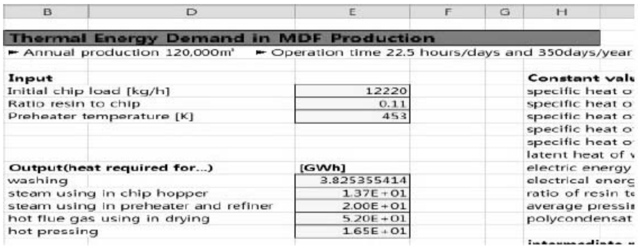


Figure 4.—Blow-line process. See the text for definitions of abbreviations.



B	D	E	F	G	H
Thermal Energy Demand in MDF Production					
► Annual production 120,000m³		► Operation time 22.5 hours/days and 350days/year			
Input					**Constant valu**
Initial chip load [kg/h]		12220			specific heat o
Ratio resin to chip		0.11			specific heat o
Preheater temperature [K]		453			specific heat o
					specific heat o
					specific heat o
					latent heat of v
Output(heat required for...)		**[GWh]**			electric energy
washing		3.825355414			electrical energ
steam using in chip hopper		1.37E+01			ratio of resin to
steam using in preheater and refiner		2.00E+01			average pressu
hot flue gas using in drying		5.20E+01			polycondensat
hot pressing		1.65E+01			

Figure 5.—Annual thermal energy demand modified calculating Excel file.

$$\begin{aligned}&(\dot{m}_{\text{fiber}}\left[C_{\text{p,fiber}}+\text{MC}_2C_{\text{pw}}\right]\dot{m}_4C_{\text{pv}})T_2\\&+(\dot{m}_rC_{\text{pr}}+\dot{m}_wC_{\text{pw}})T_{\text{r0}}\\&=(\dot{m}_{\text{r}}C_{\text{pr}}+\dot{m}_{\text{fiber}}\left[C_{\text{p,fiber}}+\text{MC}_3C_{\text{pw}}\right]\\&\quad+\left[\dot{m}_4+\dot{m}_{\text{evap}}\right]C_{\text{pv}})T_3+\dot{m}_{\text{evap}}\Delta H_{\text{wv}}\end{aligned} \tag{11}$$

$$\text{MC}_3=\frac{\dot{m}_{\text{w}}+\dot{m}_{\text{fiber}}\,\text{MC}_2+\dot{m}_{\text{evap}}}{\dot{m}_{\text{fiber}}+\dot{m}_{\text{r}}} \tag{12}$$

where C_{pw} is specific heat of water (J/kgK) and C_{pr} is specific heat of urea-formaldehyde resin (J/kgK).

Figure 6 shows the current annual thermal energy demand for production of 120,000 m^3/yr of regular MDF. The calculated results of total thermal energy demand is 115 GWh, which is 3 percent less than the results of Li et al. (2007; Fig. 1). The difference in calculated thermal energy for the hot pressing process is –2.9 percent, for the preheater and refining process is +3 percent, and for fiber drying process is –3.7 percent. The difference for each process compared with Figure 1 is less than 1 percent and is quite consistent with Li et al. (2007). Therefore, the present thermal energy calculation accuracy may be the same as that of Li et al. (2007), which is approximately –17 to 6 percent, but with less energy demand.

Economic Benefit of the Use of Recycled Fiber

Thermal energy demand and cost of recycling

Numerous investigations have been conducted on recycling MDF in which waste MDF is first shredded and after that heated at 90°C to 100°C to weaken the resin bonding.

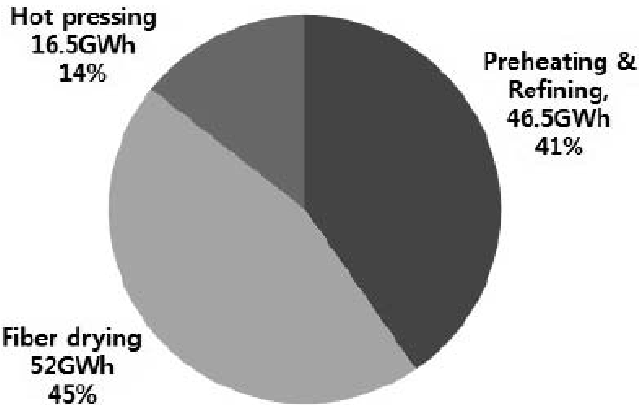


Figure 6.—Annual thermal energy demand by unit operation for production of 120,000 m^3/yr of regular medium-density fiberboard using flue gas for fiber drying from modified calculating.

Two investigations are as follows. Waste MDF chips are fed to the pressure vessel and heated by steam at 122.3 to 170.3 kPa (Sandison 2002) and heating waste MDF chips by ohmic heating in the temperature range of 80°C to 99°C (New 2011). In the patents by Roffael (1997) and Nakos (2000), they also used a preheater for waste MDF. Manufacturing MDF with virgin wood requires a higher temperature (170°C to 180°C) than recycled MDF, which requires only 100°C to resolve the resin waste of MDF in the preheater. Defibration of the waste MDF proceeds by the rapid depressurization at the exit of the blow line without refining (New 2011). If the refining process is applied, the separated fibers will be cut and the fiber length becomes shorter, resulting in a loss in fiber properties. As a result, when recycling MDF, only a pipe connecting the preheater and blow line is needed.

By lowering the operating temperature of the preheater by 10°C, the thermal energy demand in the preheater is calculated as shown in Table 2. At present, heating oil is the energy source and the fuel cost is calculated by the heating oil cost per unit energy ($0.09/kWh) in the United Kingdom in 2013. A complete schematic process of waste MDF recycling is shown in Figure 7.

From the thermal energy demand in the recycling process, the preheater operating temperature is decreased to 100°C and the refining process is excluded. The annual thermal energy demand for recycling is reduced to approximately 70 GWh, which is approximately 39 percent less energy than the original MDF production. The main energy savings comes from the preheater and refining process, which required 46.5 GWh for virgin material but only 1.5 GWh for waste MDF. The cost of recycled fiber can be estimated by counting the thermal energy cost, which depends on the oil price.

Cost–benefit with mixing recycled fiber

Recycled fiber can be used in MDF production by mixing with virgin fiber (Roffael 1997, Beele 2009). The cost–benefit is estimated when recycled fiber is used as a substitute for virgin fiber after defibration. The cost for making fibers is based on the thermal energy demand and heating oil price.

As a result, when recycled fibers are substituted for 10 and 20 percent of the original wood supply, the reduction in the cost of virgin wood material and thermal energy savings are shown in Table 3. It is estimated that if 10 percent waste MDF is used to produce MDF, the price of virgin wood

Table 2.—Effect of operating temperature on annual thermal energy demand in preheater and cost for 120,000 m^3/yr for regular medium-density fiberboard.

Preheater temperature (K)	Energy demand in preheater (GWh)	Price of heating oil (US$, millions)
453	25.1	2.259
443	22.1	1.989
433	19.2	1.728
423	16.5	1.485
413	13.3	1.197
403	10.3	0.927
393	7.38	0.6642
383	4.43	0.3987
373	1.48	0.1332

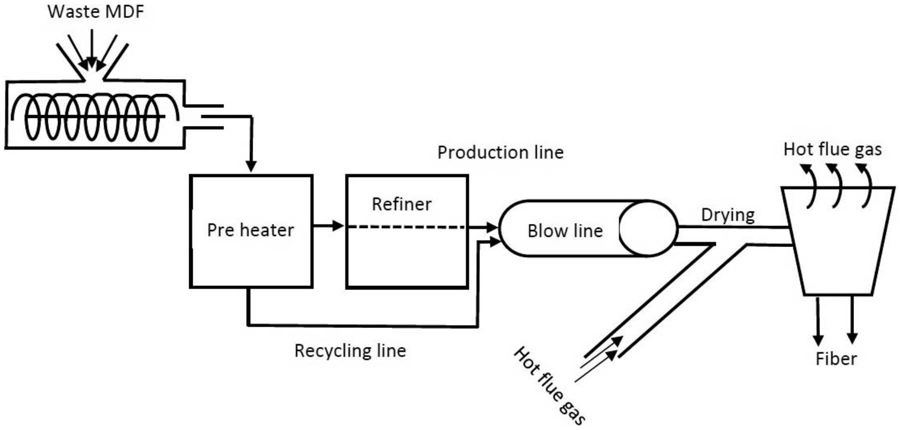


Figure 7.—Schematic of waste medium-density fiberboard (MDF) recycling.

Table 3.—Annual thermal energy demand for 120,000 m^3/yr medium-density fiberboard with recycled fiber.

Recycled fiber:wood	Wood supply (t)	Energy demand in pressing (GWh)	Energy savings (%)
0:1	90,000	115	0.0
1:9	81,000	110.5	−3.9
2:8	72,000	106	−7.8

material is reduced by 10 percent and there is approximately 3.9 percent energy savings. When 20 percent waste MDF is used, the price of virgin wood material is reduced by 20 percent and there is approximately 7.8 percent energy savings.

The price of waste MDF is not assumed in this study, but at the present time, the incineration cost or landfill charge for waste MDF is much higher than the cost to buy it. If an MDF company gets some money to pick up the waste MDF material, the benefit will increase more. Not only will the cost–benefit ratio improve, but the recycled MDF will reduce the demand of virgin wood material and also reduce environmental problems such as global warming.

Conclusions

In this study, the thermal energy requirement of the MDF production process is compared with previous studies and the results are in good agreement. Using this prediction method, thermal energy required to manufacture MDF using recycled fibers is calculated. The recycling method is a high-temperature treatment in a preheater at an operating temperature of 100°C, which melts the resin to separate the fibers. The virgin wood material cost–benefit ratio and the energy reduction required are calculated for MDF manufactured by replacing 10 and 20 percent, respectively, of the wood fiber with recycled fiber. Results show that the benefits of MDF production using 10 percent recycled fiber result in a 10 percent reduction in virgin wood material cost and an energy savings of 3.9 percent. Using 20 percent recycled fiber, a 20 percent reduction in virgin wood material cost and an energy savings of 7.8 percent in MDF production are estimated. The recycled MDF will reduce the demand of virgin wood material and also reduce environmental problems such as global warming.

Acknowledgment

The authors are grateful for the financial support from Korea Forest Service grant no. 2015077D10-1718-AA01.

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