Int J Life Cycle Assess (2018) 23:957–969
DOI 10.1007/s11367-017-1343-6

WOOD AND OTHER RENEWABLE RESOURCES

Life cycle assessment of wood-based boards produced in Japan and impact of formaldehyde emissions during the use stage

Katsuyuki Nakano[1] · Keisuke Ando[2] · Mitsuo Takigawa[3] · Nobuaki Hattori[2]

Received: 14 September 2016 / Accepted: 24 May 2017 / Published online: 6 June 2017

Abstract

Purpose This study aims to conduct a comprehensive life cycle assessment (LCA) of wood-based boards to support environmentally conscious design. The goal is achieved by the following objectives: to produce generic LCA data for production of wood-based boards (cradle-to-gate) and to evaluate the human health impacts through life cycle including the use stage (cradle-to-grave), based on the latest regulations for formaldehyde emissions in Japan.

Methods Production data of particleboard (PB), hard fiberboard (HB), medium-density fiberboard (MDF), and insulation fiberboard (IB) were obtained from major manufacturers of wood-based boards in Japan. We evaluated the impact categories of climate change, abiotic resource depletion, human toxicity (cancer and non-cancer effects), and ecotoxicity (cradle-to-grate assessment). For the human health impacts by formaldehyde emissions from PB and MDF in the use stage (40 years), we calculated the impacts through the life cycle (cradle-to-grave assessment), at all grades of formaldehyde emission rates set by the formaldehyde regulation.

Results and discussion Cradle-to-gate assessment indicated that adhesives constituted 28–55% of the impacts in all categories for PB and MDF, whereas 74–98% of the impacts resulted from utilities supply for HB and IB. In particular, heat supply from wood boilers accounted for more than 92% of human health (non-cancer) and 71% of ecotoxicity impacts in HB. Cradle-to-grave assessment of PB and MDF, which satisfy strict regulations on formaldehyde emissions (<0.005 mg/m^2/h), demonstrated that impacts on human health (total of cancer and non-cancer effects) were decreased by more than 90% compared with a conventional product (0.15 mg/m^2/h). The production stage impacts of the products meeting the string regulations were more than half of the total owing to the lower formaldehyde emissions in the use stage.

Conclusions Generic LCA data for wood-based board production (cradle-to-gate) in Japan are calculated. Significant impacts are adhesives for PB and MDF and utility supply for HB and IB. The cradle-to-grave assessment of PB and MDF revealed that shifting to low-formaldehyde emission products has markedly reduced impacts on human health. We recommend preferentially improving the environmental performance of the production process of wood-based boards in countries with strict regulations on formaldehyde emissions.

Keywords Hard fiberboard · Human health · Insulation fiberboard · Medium-density fiberboard · Particleboard · Regulation · Use stage

Responsible editor: Zuoren Nie

✉ Nobuaki Hattori
hattori@cc.tuat.ac.jp

[1] LCA Center, Japan Environmental Management Association for Industry (JEMAI), 2-1, Kajicho 2-chome, Chiyoda-ku, Tokyo 101-0044, Japan

[2] Faculty of Agriculture, Tokyo University of Agriculture and Technology, 5-8, Saiwai-cho 3-chome, Fuchu-shi, Tokyo 183-8509, Japan

[3] Japan Fiberboard and Particleboard Manufacturers Association, 12-9, Nihonbashi 2-chome, Chuo-ku, Tokyo 103-0027, Japan

1 Introduction

Wood has been used as a basic material for a variety of purposes for an extremely long time. Both solid wood and wood-based boards such as plywood, particleboard (PB), and fiberboard have also been utilized because PB and fiberboards can increase the stability of the mechanical characteristics of wood. Furthermore, wood-based boards can be produced from low-quality wood materials such as thinning residues and demolition wood; therefore, the yield of the production process is high compared with that of solid lumber. PB is made of wood particles by hot-pressing after spreading adhesives (Japanese Standards Association 2015); fiberboard is formed from wood fibers. The Japanese industrial standard (JIS) classifies fiberboards into hard fiberboard (HB), medium-density fiberboard (MDF), and insulation board (IB) on the basis of their density and production method (Japanese Standards Association 2014). These wood-based boards are utilized as materials for various products, such as buildings, furniture, automotive interiors, and packaging. A total of 1.9 million m^3 of these four types of wood-based boards (PB, HB, MDF, and IB) were produced in Japan in 2013 (Ministry of Economy Trade and Industry 2016). Therefore, the generic life cycle assessment (LCA) data of wood-based boards are highly necessary. For example, in an LCA case study of a wooden wardrobe, the largest environmental impact was induced by the particleboard production process (Iritani et al. 2015).

Several LCA case studies of the production of wood-based boards have been performed, such as on PB in Spain (Rivela et al. 2006), the USA (Wilson 2010), Brazil (Silva et al. 2014), and Iran (Kouchaki-Penchah et al. 2016). Furthermore, MDF produced in Spain and Chile (Rivela et al. 2007), Brazil (Silva et al. 2013), and Iran (Kouchaki-Penchah et al. 2015) and HB produced in Europe (González-García et al. 2009) have been studied. However, no LCA studies of Japanese wood-based board have been published. Silva et al. (2013) determined that the environmental impact of MDF produced in Brazil was significantly different from that produced in Europe and the USA, because natural gas was used as the main thermal energy source in Europe and the USA whereas heavy fuel oil and wood residues were used in Brazil. In addition, recycled wood was the main material in both Europe and the USA, whereas in Brazil, material was obtained from a dedicated forest (Silva et al. 2013). The ratio of recycled wood to virgin wood was a major parameter in the ecological footprint of wood-based board (Saravia-Cortez et al. 2013). Therefore, regional characteristics should be taken into account when evaluating wood-based boards.

These previous studies provided useful background data on wood-based boards; however, an assessment throughout a product life cycle is needed to consider overall optimization. Therefore, LCA studies including use and end-of-life stages have also been carried out. For example, a study of PB made from sugarcane bagasse (*Saccharum* spp.) and pine wood (*Pinus elliottii*) shavings suggested that the PB production stage had the largest impact for human toxicity for both materials (Santos et al. 2014). However, that study evaluated the impacts of PB processing (e.g., electric saws) but excluded formaldehyde emissions during the use stage.

Chemical substances such as formaldehyde are used for adhesive materials in the production stage, and a part of these chemicals do not react and remain in the product. These unreacted chemicals will be emitted in the use stage: indoor emissions of these chemicals readily result in human exposure. Formaldehyde causes cancer of the nasopharynx and leukemia and is suspected to cause sinonasal cancer (International Agency For Research on Cancer 2012). In a case study of a chair, formaldehyde emitted in the use stage had the largest impact on human health over the life cycle (Skaar and Jørgensen 2013). Similarly, Chaudhary and Hellweg (2014) quantified a variety of volatile organic compound (VOC) emissions in the use stage and concluded that more than 90% of the total impact to human health was induced by formaldehyde emissions during the use stage. That study used data from 50 studies published between 1967 and 2012; however, regulations on formaldehyde emissions from wood-based boards have been introduced and strengthened in a number of countries (Salem and Böhm 2013). Thus, the effects of formaldehyde emissions in the use stage on human health may have changed and should be re-assessed based on the latest regulations.

It has been recommended that indoor exposure should be routinely addressed within LCA (Hellweg et al. 2009). The second version of the life cycle impact assessment method based on endpoint modeling (LIME2) included characterization factors for evaluating indoor emissions (Itsubo and Inaba 2014). The characterization factors of LIME2 were calculated based on the ratio of exposure efficiency and the daily human limit value, with reference to the characterization factors of toxic chemicals (Itsubo and Inaba 2014). Furthermore, the USEtox model, an impact assessment method for human health and freshwater ecosystems, was also extended to include impact factors for indoor emissions (Rosenbaum et al. 2015). These methods facilitate consistent assessment of human health aspects through a product's life cycle.

In the production stage of several wood-based boards, adhesives such as urea formaldehyde (UF) resin and melamine formaldehyde resin are used. As these adhesives are synthesized for wood-based board, the characterizations of these environmental impacts should be considered in an LCA study (e.g., Silva et al. 2013). Therefore, LCA studies focusing on adhesives for wood-based boards have also been conducted (Sawada et al. 2006; Silva et al. 2015). In addition, improvements in adhesive environmental performance have been evaluated by LCA (McDevitt and Grigsby 2014). Therefore, the amounts and types of adhesives used in production of wood-based boards and the composition of each adhesive type should be assessed to carry out an appropriate LCA study of a wood-based board.

Taking these issues into consideration, one goal of this study was to produce generic LCA data for production of a wood-based board (cradle-to-gate) in Japan. Another goal was to evaluate the human health impacts of wood-based board life cycle (cradle-to-grave) considering the latest regulations on formaldehyde emissions in the use stage. By utilizing these results, we aim to identify the processes that are significant in producing environmentally conscious design of a wood-based board. PB, HB, MDF, and IB were evaluated because almost all wood-based boards produced in Japan (except plywood) can be classified as one of these.

2 Material and methods

The properties of the evaluated wood-based boards and their production processes are summarized in Table 1 and Fig. 1, respectively. In Japan, approximately 1 million m^3 of PB and 0.8 million m^3 of fiberboards (HB, MDF, and IB) are produced annually. PB and MDF are produced using a dry process whereas HB and IB use a wet process; therefore, the HB and IB production processes consume a larger amount of water than those of PB and MDF. In contrast, PB and MDF require greater amounts of adhesives than do HB and IB. As adhesives use formaldehyde, some of the formaldehyde used will be emitted during the production and use stages.

To obtain generic LCA data for wood-based boards in Japan, a functional unit was defined as 1.0 m^3 production of each wood-based board in the cradle-to-gate assessment. For assessments including use and end-of-life stages (cradle-to-grave assessment), a functional unit was defined as 16-mm-thick wood-based boards with an exposed surface area of 7.0 m^2 and a service life of 40 years (Table 2). This is the same as the definition used by Chaudhary and Hellweg (2014).

2.1 System boundaries

We evaluated two cases: one from resource acquisition to wood-based board production (cradle-to-gate), the other from resource acquisition to the use and end-of-life stages (cradle-to-grave; Fig. 2). The environmental impact of the production stage included adhesive production and generation of electricity used in the production stage. To evaluate recycled wood material, the cut-off method (Ekvall and Tillman 1997) was adopted. The cut-off method excludes the environmental impact of recycled material prior to recycling from the system boundary. Therefore, transportation of used material and preprocessing of wood material were evaluated as environmental impacts of recycled wood material. Wood material from forest thinning was evaluated as virgin material, and the environmental impact of forest management was included in the system boundary. During the use stage, wood-based boards do not consume energy but emit formaldehyde to the indoor atmosphere. In the end-of-life stage, used wood-based boards are recycled in compliance with the

Table 1 Summary of the types of wood-based board evaluated and the data collected

	Particleboard	Hard fiberboard	Medium-density fiberboard	Insulation fiberboard
Standard	JIS A 5908:2015	JIS A 5905:2014	JIS A 5905:2014	JIS A 5905:2014
Density defined by the standard (ρ)	0.40 $g/cm^3 \le \rho <$ 0.90 g/cm^3	0.80 $g/cm^3 \le \rho$	0.35 $g/cm^3 \le \rho <$ 0.80 g/cm^3	$\rho <$ 0.35 g/cm^3
Production in Japan in 2013				
Volume (1000 m^3)	1041	48	404	399
Area (1000 m^2) in specified thickness	67,618	16,596	58,355	40,205
Average density (estimation)	0.75 g/cm^3	0.85 g/cm^3	0.72 g/cm^3	0.32 g/cm^3
Functional unit(cradle-to-gate)	1.0 m^3	1.0 m^3	1.0 m^3	1.0 m^3
Data source (production share in Japan)	6 factories (>50%)	3 factories (>50%)	2 factories (>60%)	3 factories (>80%)
Time of raw data collected				
Material and energy	Apr. 2004 to Mar. 2005	Apr. 2005 to Mar. 2006	Apr. 2009 to Mar. 2010	Jun. 2007 to May 2008
Chemicals emission	Apr. 2013 to Mar. 2014	Apr. 2013 to Mar. 2014	Apr. 2013 to Mar. 2014	Apr. 2013 to Mar. 2014
Wood material composition	Apr. 2013 to Mar. 2014	Apr. 2014 to Mar. 2015	Apr. 2014 to Mar. 2015	Apr. 2014 to Mar. 2015
Water consumption	Oct. 2014 to Sep. 2015	Apr. 2015 to Mar. 2016	Apr. 2015 to Mar. 2016	Apr. 2015 to Mar. 2016

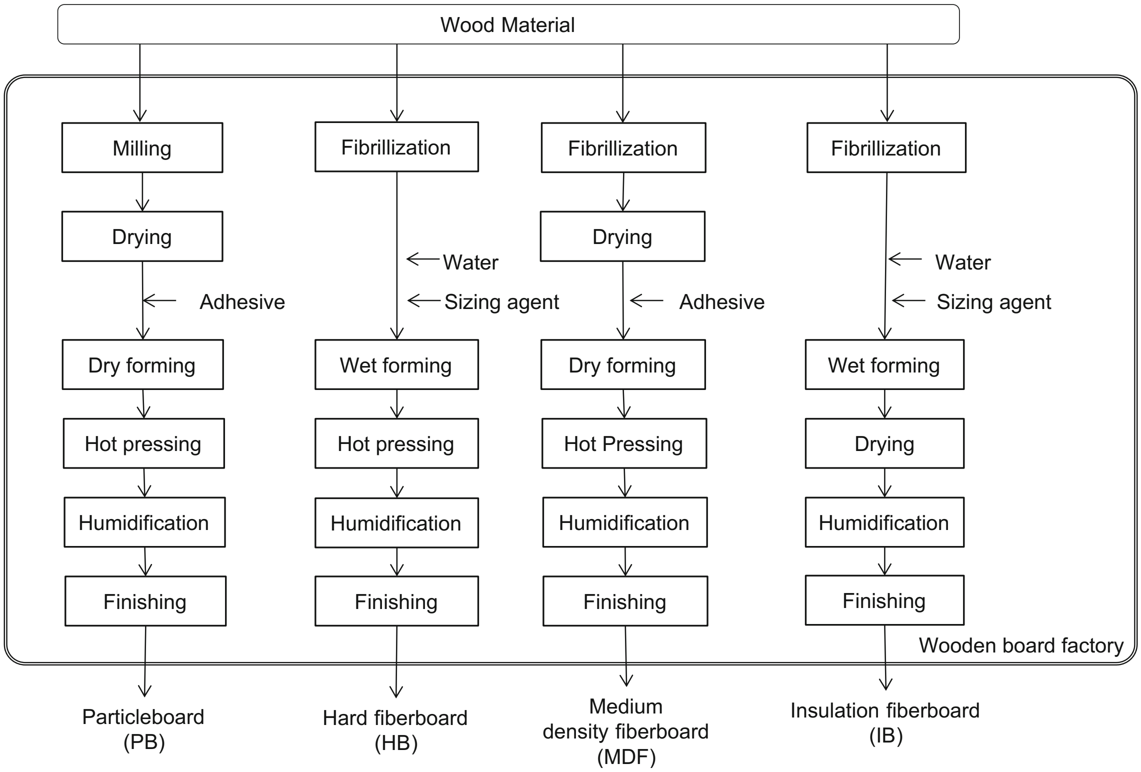


Fig. 1 Production processes of the different types of wood-based board

Construction Material Recycling Law; therefore, the recycling process was included in the system boundary. Typical recycling methods are material recycling and heat recovery. In both methods, used wood-based boards are shredded and initially sorted into wood and other materials (e.g., metal). The sorted wood is, in general, valuable material and is sold as recycled wood; thus, further downstream flow of this material was treated as cut-off in the analysis.

Wood capture carbon from the atmosphere and wooden products store it during their use stage; however, the impact of temporal carbon storage on climate change was not considered since these CO_2 will be emitted in the end-of-life stage (e.g., heat recovery). We adopted the method, as with the previous studies (Rivela et al. 2007; Santos et al. 2014; Kouchaki-Penchah et al. 2015).

2.2 Data collection

2.2.1 Production stage

Major manufacturers of wood-based boards in Japan have collected input and output data on their production processes (Table 3). Overall, these manufacturers account for more than 50% of the total production of each wood-based board type. Material and energy input data were obtained from 2005 to 2010, and we confirmed with the manufacturers that the production processes were almost the same in 2016. The composition of wood material sources has changed; therefore, these data were updated. To satisfy regulations on formaldehyde emissions, chemicals, so-called formaldehyde scavengers, were used in the production process. However, these chemicals were not included in this study because they contain

Table 2 Goal and functional unit

	Cradle-to-gate	Cradle-to-grave
Goal	- produce generic LCA data in Japan - support environmentally conscious design	- clarify an achievement of formaldehyde emission regulation
Evaluated wood-based board	PB, HB, MDF, IB	PB
Functional unit	1.0 m^3	16-mm-thick wood-based boards with an exposed surface area of 7.0 m2 and a service life of 40 years

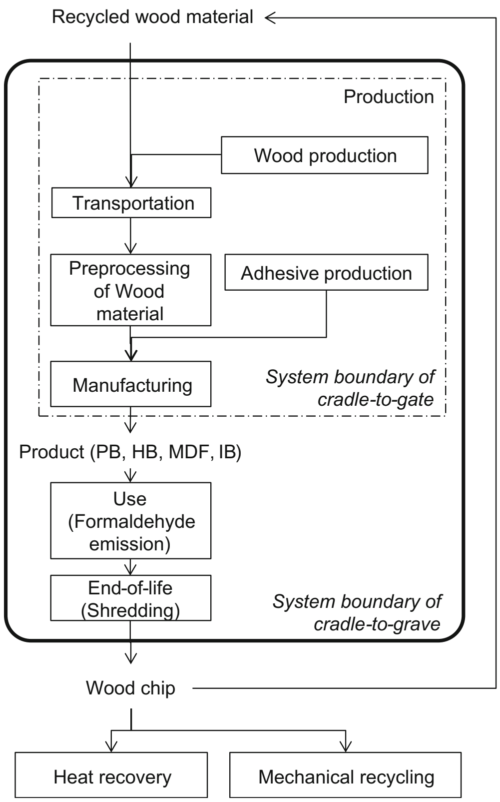


Fig. 2 Systems boundaries of cradle-to-gate assessment and cradle-to-grave assessment

only small quantities (less than 0.1 wt%) of active ingredients. Similarly, other inputs (e.g., packaging material) that made up less than 0.1 wt% were cut-off. The law concerning the Pollutant Release and Transfer Register (the PRTR law) requires manufacturers to report the amounts of chemicals emitted from their factories. Therefore, we used the data reported for the PRTR law (Ministry of the Environment Japan 2016) and annual wood-based board production (Ministry of Economy Trade and Industry 2016) to quantify the amount of chemical emissions from the production processes.

Wood material is purchased from a variety of sources, such as demolished buildings and residue from factories making wooden products. Therefore, the Japan Fiberboard and Particleboard Manufacturers Association surveyed wood material sources in 2014 (Table 4). The production processes of HB and IB are similar and both types of board are manufactured in the same factory; thus, for wood material composition, the same data were used for HB and IB.

As a preliminary study, we analyzed ash about chromium VI (JIS K 0102:2013, 65.2.6), chrome (JIS K 0102:2013, 65.1.4), and arsenic (JIS K 0102:2013, 61.3). The ash samples were taken from eight industrial wood boilers. However, representativeness of the data was low, and these data were not used for the inventory analysis but used only for the discussion.

2.2.2 Use stage

Most wood-based boards become building materials after processing to make them suitable for various applications. MDF, for example, is laminated on the surface by a resin film and is

Table 3 Inventory data for the production processes of wood-based boards

			PB	HB	MDF	IB
Input	Material	Wood chip (kg)	7.95×10^{2}	8.93×10^{2}	7.98×10^{2}	3.01×10^{2}
		Urea–formaldehyde resin (kg)	3.50×10^{1}		7.83×10^{1}	
		Melamine–formaldehyde resin (kg)	2.39×10^{1}			
		Melamine–urea–formaldehyde resin (kg)			5.32×10^{1}	
		Phenol–formaldehyde resin (kg)	1.61×10^{1}	1.20×10^{1}		1.09×10^{1}
		Methylene diphenyl diisocyanate (kg)	9.30		1.84×10^{1}	
		Paraffin wax (kg)		1.31×10^{1}	9.58	1.14×10^{1}
		Aluminum sulfate (kg)				3.18
	Energy and water	Electricity (kWh)	1.82×10^{2}	2.41×10^{2}	2.82×10^{2}	1.64×10^{2}
		Diesel oil (L)	8.85×10^{-1}	1.08	6.77×10^{-1}	
		Heavy oil (L)	1.85×10^{1}	2.25×10^{1}		1.55×10^{1}
		Urban gas (m^3)	8.63		3.42×10^{1}	7.68
		Wood fuel (kg)	1.20×10^{2}	5.36×10^{2}	1.11×10^{2}	1.42×10^{2}
		Water (m^3)	1.04	5.05	1.44	2.32
	Transport	4-t truck (tkm)	5.75×10^{-2}	5.45	1.69	6.88×10^{-2}
		10-t truck (tkm)	1.45×10^{1}	4.30×10^{1}	1.69×10^{1}	3.58×10^{1}
		15-t truck (tkm)				1.66×10^{-1}
		Bulk carrier (tkm)			3.50×10^{3}	3.23×10^{1}
Output	Product (m^3)		1.00	1.00	1.00	1.00
	Emission to air	Formaldehyde (kg)	1.72×10^{-2}		1.63×10^{-2}	
		Methyl chloride (kg)	6.63×10^{-6}		8.91×10^{-4}	
		Phenol (kg)	6.73×10^{-7}			
		n-Hexane (kg)			7.42×10^{-5}	
		1,2,4-Trimethylbenzene (kg)			2.72×10^{-5}	
		Xylenes (kg)	2.59×10^{-6}		3.71×10^{-5}	
		Methylnaphthalene (kg)				
		Maleic anhydride (kg)				
	Waste	Ash (for landfill; kg)	1.66×10		5.35	3.04×10^{1}

Table 4 Wood material sources of wood-based boards in 2014

Unit: %	PB	HB	MDF	IB
Thinned wood	2	13	24	13
Residue from wooden-products factories (e.g., plywood and saw mill)	15	30	64	30
Recycled from used building material	83	57	12	57
Total	100	100	100	100

used as the base material for decorative sheets. In this study, however, we focused on the wood-based boards themselves, excluding the environmental impacts of these sub-materials and processing. In the use stage, formaldehyde constituted the majority of the impact to human health in the total impacts. The impacts of other VOCs are relatively small (Chaudhary and Hellweg 2014); thus, this study focused on formaldehyde emissions during the use stage.

The issue of formaldehyde emissions in the use stage has become a matter of concern owing to increasing air-tightness of buildings. In Japan, a standard for formaldehyde emission rates (FE; mg/m^2/h) for wood-based boards was established in 1980, but without associated regulations. In 1997, the Japanese Government produced an indoor concentration guideline. In 2003, the Building Standards Law was amended to prohibit use of building materials that emit more than 0.12 mg/m^2/h of formaldehyde in living rooms (Table 5). Furthermore, use of F-2 stars and F-3 stars materials in living areas is restricted. As a result of these rigorous laws, most wood-based boards currently produced in Japan are F-4 stars and the share of F-4 stars material has been increasing (Fig. 3). Formaldehyde data for HB and IB were excluded from the survey because almost no formaldehyde is used in the production process of these materials: in fact, HB and IB are excluded from the regulations. The amount of formaldehyde emitted during the use stage depends on the grade of the formaldehyde regulation; therefore, formaldehyde emissions of PB and MDF were calculated for each grade of regulation in this study.

In a constant environment, FE rapidly decreases at an early stage, with a subsequent gentle decrease over a long time (Chaudhary and Hellweg 2014; Zinn et al. 1990). Chaudhary and Hellweg (2014) assessed appropriate models to express the relation of FE with elapsed time and concluded that a dual first-order decay model (Brown 1999) performed the best in representing long-term emissions. However, other models, such as a log time model (Zinn et al. 1990) and a second-order model (Skaar and Jørgensen 2013), also exhibited good fit (average $R^2 > 0.8$).

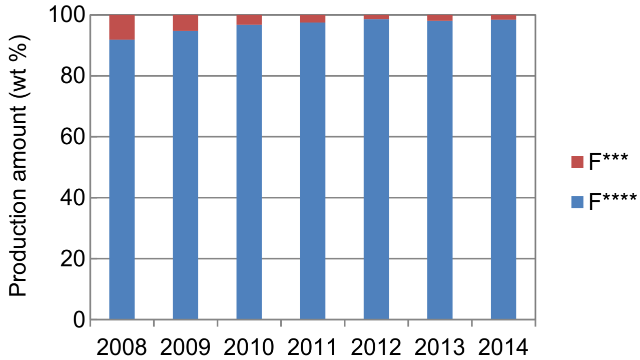
The dual first-order model consists of two parameters that express short- and long-term emissions (Brown 1999). Formaldehyde emissions in the "fresh" phase were regarded as having been emitted during the production stage because they were reported as emissions from the factory under the PRTR law. The standards (Japanese Standards Association 2001) require measurement of formaldehyde emissions after conditioning (usually 1 week). To focus on long-term emissions, we adopted the log time model to model the temporal changes in FE. Zinn et al. (1990) surveyed the long-term temporal changes of FE from a variety of wood-based boards and concluded that the average half-life in the log time model was 216 days. Using this value and the initial FE of each grade defined by the law, we modeled temporal changes in FE (Fig. 4).

Table 5 Grades and regulations of formaldehyde emissions from wood-based boards in Japan

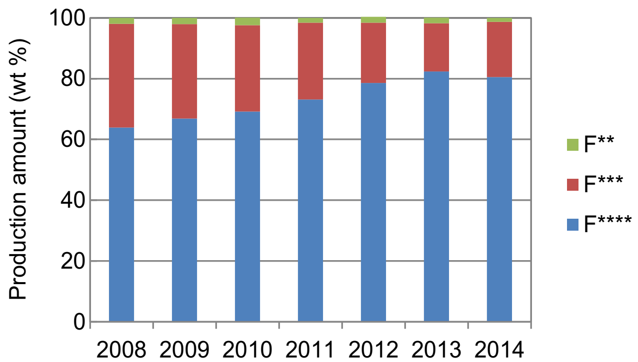
Grade	Formaldehyde emission rate (FE; default value used for this study)	Regulation[a]
F-1 star (F*)[b]	0.12 mg/m^2/h < FE (0.15 mg/m^2/h)	Prohibited
F-2 stars (F**)	0.02 mg/m^2/h < FE ≤ 0.12 mg/m^2/h (0.07 mg/m^2/h)	Limited to approved areas of use
F-3 stars (F***)	0.005 mg/m^2/h ≤ FE < 0.02 mg/m^2/h (0.0125 mg/m^2/h)	Limited to approved areas of use
F-4 stars (F****)	FE < 0.005 mg/m^2/h (0.004 mg/m^2/h)	Not restricted

[a] Regulation of the Building Standards Law for living rooms in Japan

[b] F-1 star grade is no longer used owing to the amendment of the Building Standards Law in 2003



(a) Particleboard



(b) Medium-density fiberboard

Fig. 3 Proportions of each regulation grade in wood-based board production in Japan. Data from the Japan Fiberboard and Particleboard Manufacturers Association

The total amount of formaldehyde emitted during the use stage (m_{tot}) was calculated using Eq. (1):

$$m_{tot} = \int EF(t)dt \tag{1}$$

where EF(t) is FE (kg/m^2/h). The total use period was assumed to be 40 years (the same as that of Chaudhary and Hellweg 2014), and the total formaldehyde emissions were calculated to be 1.64×10^{-2} kg/m^2 (F-1 star), 7.66×10^{-3} kg/m^2 (F-2 stars), 1.37×10^{-3} kg/m^2 (F-3 stars), and 4.38×10^{-4} kg/m^2 (F-4 stars).

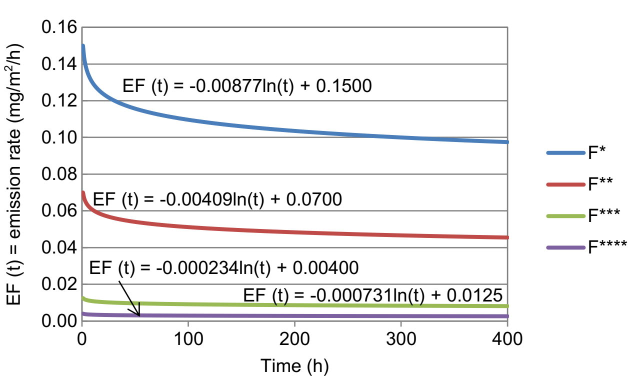


Fig. 4 Temporal changes in formaldehyde emission rates. EF(t): formaldehyde emission rates (kg/m^2/h)

2.2.3 End-of-life stage

Used wood-based boards were transported from the building to a recycling plant. It was assumed that the boards were transported for 100 km by a 4-t truck, shredded, and sorted into wood and other materials such as metal. Subsequently, as the sorted wood is, in general, valuable material, further down-stream flow of the wood was treated as cut-off.

2.2.4 Background data

For background data, generic environmental data of materials and energy, the cut-off system model ecoinvent v.3.2 (Wernet et al. 2016) was used. To increase data quality, inventory data of adhesives for wood-based boards were calculated using gate-to-gate data for adhesive production (Sawada et al. 2006) and ecoinvent v.3.2. Inventory data for polyvinyl alcohol (PVA), which is one of the materials of UF resin, were not available in ecoinvent v.3.2; thus, IDEA v.1.1 (Tahara et al. 2010) was used to evaluate PVA. IDEA v.1.1 (Tahara et al. 2010) is the Japanese process-based LCA database, which has a geographical representativeness higher than that of ecoinvent v.3.2; however, the comprehensiveness of elementary flows for evaluating human health impacts is lower than that of ecoinvent v.3.2. There was some concern over underestimation of the impact of PVA; however, the amount of PVA used was small (1.57×10^{-2} kg/kg urea–formaldehyde resin), and the influence on the total life cycle was thus judged to be insignificant.

2.3 Impact assessment method

The impact categories of climate change, abiotic resource depletion, human toxicity (cancer effects and non-cancer effects), and ecotoxicity were evaluated in this work. To evaluate the impact for climate change, the latest version of global warming potentials (100-year time horizon; Myhre et al. 2013) was adopted. For abiotic resource depletion, we used characterization factors based on ultimate reserves and extraction rates (CML; Guinée et al. 2002).

The USEtox model was developed under the auspices of the UNEP/SETAC Life Cycle Initiative and incorporates a broad scientific consensus (Hauschild et al. 2008; Rosenbaum et al. 2008). The model (Rosenbaum et al. 2015) has been used to evaluate human toxicity (cancer and non-cancer effects) and ecotoxicity. USEtox 2.01 models the impacts of chemical substance emissions on household and industrial indoor air and is suitable for evaluating chemical emissions during the production and use stages in this study. Formaldehyde emissions in the production stage were evaluated using the characterization factor of emissions for industrial indoor air; emissions during the use stage were evaluated as for household indoor air. Chaudhary and Hellweg (2014) adopted the previous USEtox model (Rosenbaum et al. 2008), and so our results can be compared with theirs to a certain extent. These selected characterization models were also recommended for LCA studies by Hauschild et al. (2013).

3 Results

3.1 Cradle-to-gate

The results of each impact category indicator (Table 6) and the composition of these indicators (Fig. 5) clarified the differences in environmental impacts between the evaluated wood-based boards. Adhesives occupied 28–55% of impacts in all impact categories for PB and MDF; in contrast, 74–98% of impacts were caused by utilities supply for HB and IB. In particular, heat supplied by wood boilers contributed 92 and 76% of human health (non-cancer) and 71 and 43% of ecotoxicity for HB and IB, respectively. PB and MDF production processes utilized wood boilers to the same extent as IB processes; however, PB and MDF used larger amounts of adhesives and so the impacts of adhesives decreased the wood boiler share of total impacts. Zinc emitted to the atmosphere from wood boilers and chromium VI in discharged water from landfilled wood ash were the main contributions to the results for human health (non-cancer) and ecotoxicity, respectively.

It should be noted that these results did not indicate that a certain type of wood-based board is environmentally friendly, because each type of board has a different function and application. Therefore, comparisons of absolute values were avoided in this study.

3.2 Cradle-to-grave

By shifting from F-1 star products to F-4 stars products, the impacts to human health (total of cancer and non-cancer effects) were dramatically decreased (Fig. 6). Approximately 90% of human health impacts occurred in the use stage for F-1 star and F-2 stars products, in good agreement with the results of Chaudhary and Hellweg (2014). In contrast, the impacts of the production stage for the F-4 stars products were more than half of the total owing to the lower formaldehyde emissions in the use stage. Chaudhary and Hellweg (2014) calculated the formaldehyde emissions in the use stage (40 years) as 4.10×10^{-3} kg/m^2 (PB) and 3.30×10^{-3} kg/m^2 (MDF) based on literature values from 50 studies published between 1967 and 2012. These values might be classified in the F-2 stars grade because we modeled the formaldehyde emission of the F-2 stars as 7.66×10^{-3} kg/m^2 and that of the F-3 stars as 1.37×10^{-3} kg/m^2.

Chaudhary and Hellweg (2014) converted the characterization results of human health (cancer effects and non-cancer effects) into disability-adjusted life years (DALY) using the values 11.5 DALY/CTU$_h$ for cancer effects and 2.7 DALY/CTU$_h$ for non-cancer effects (Huijbregts et al. 2005). For human health impacts of the production and end-of-life stages of PB, for example, Chaudhary and Hellweg (2014) obtained a value of 3.52×10^{-5} DALY (95% confidence interval 2.15×10^{-6} to 8.20×10^{-4} DALY). Using the same method, our result for PB was also converted to DALY and calculated to represent 7.79×10^{-5} DALY. Our value was larger than that of Chaudhary and Hellweg (2014) but falls within their confidence interval. This study used ecoinvent 3.2 whereas Chaudhary and Hellweg (2014) applied ecoinvent 2.2: this affected the results because ecoinvent 3.1 tends to provide higher environmental impacts than does ecoinvent 3.2 (Steubing et al. 2016). Intrinsically, there are large

Table 6 Impact assessment results for wood-based boards

Impact category	LCIA method	Unit (/m^3)	PB	HB	MDF	IB
Climate change	100a (Myhre et al. 2013)	kg CO_2 eq.	4.44×10^2	3.31×10^2	8.50×10^2	2.35×10^2
Abiotic resource depletion	CML (Guinée et al. 2002)	kg Sb eq.	4.32	3.18	8.24	2.12
Human toxicity—cancer effects	USEtox[a]	CTU$_h$	1.70×10^{-5}	1.35×10^{-5}	3.24×10^{-5}	8.88×10^{-6}
Human toxicity—non-cancer effects	USEtox[a]	CTU$_h$	1.55×10^{-4}	3.98×10^{-4}	2.31×10^{-4}	1.28×10^{-4}
Ecotoxicity	USEtox[a]	CTU$_{eco}$	1.64×10^3	2.15×10^3	2.94×10^3	9.36×10^2

LCIA life cycle impact assessment, *CTU$_h$* comparative toxicity unit for human health, *CTU$_{eco}$* comparative toxicity unit for ecotoxicity

[a] Rosenbaum et al. (2015) was used for indoor emissions and Rosenbaum et al. (2008) was used for other emissions

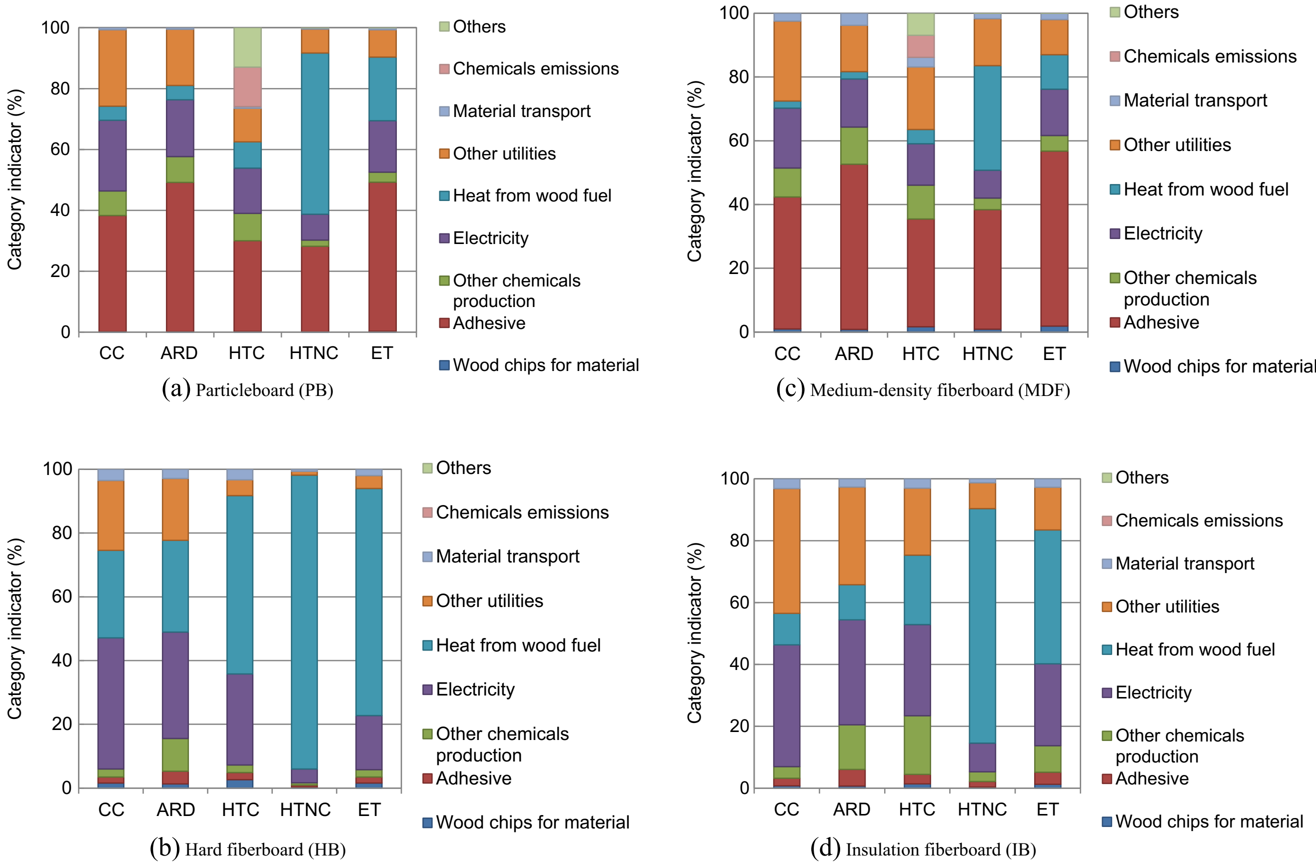


Fig. 5 Cradle-to-gate environmental impact assessment results. *CC* climate change, *ARD* abiotic resource depletion, *HTC* human toxicity—cancer effects, *HTNC* human toxicity—non-cancer effects, *ET* ecotoxicity

uncertainties in the LCA results in terms of human health (Rosenbaum et al. 2008); thus, the differences in human health impact for the production and end-of-life stages between these studies were not significantly large.

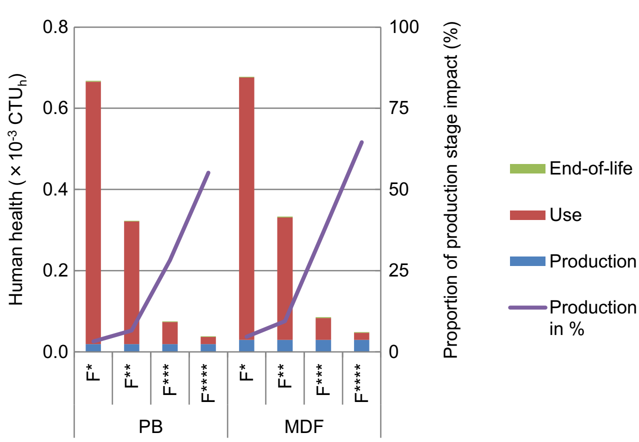


Fig. 6 Cradle-to-grave assessment result of impacts on human health (total of cancer and non-cancer impacts). Formaldehyde emissions in the use stage were estimated using a log time model (Zinn et al. 1990). Functional unit 7 m^2 of 16-mm-thick wood-based board with a service life of 40 years

4 Discussion

4.1 Human health impact in the production stage

Regarding impacts to human health (non-cancer effects), "heat from wood fuel" occupied the largest share (33–92%). This parameter was also the main contributor to ecotoxicity for IB and HB. "Zinc emissions to air (high population density)" was a major elementary flow affecting human health (non-cancer effects), as was "chromium VI emissions to ground water (long-term)" for ecotoxicity. The emissions of these elementary flows were not measured in this study but were calculated from the background database (ecoinvent). In ecoinvent, most of these elementary flows were emitted when wood fuel was incinerated and after ash was landfilled; thus, these flows could be excluded from this study if zinc was not included in the wood fuel used in the boilers and chromium VI was not present in the ash.

In Japan, boilers are regulated with respect to a variety of emissions, including heavy metals, if they incinerate waste as defined by the law. In fact, the producers of several wood-based boards that incinerate recycled wood have measured these substances. However, for biomass boilers, only measurement of sulfur oxides, nitrogen oxides, and dust is obligatory because, as recycled wood has a market value, it is not defined as waste in general. Contaminants and/or remains of various substances (e.g., paint) may be present in recycled wood. Furthermore, zinc occurs in natural wood, especially in bark (Kofujita et al. 2005). We analyzed ash samples taken from eight industrial wood boilers: five of the samples contained chromium VI. Therefore, the current wood boiler operation satisfies the relevant laws and several producers have already measured these substances; however, quantitative elemental analysis of wood fuel and incinerated ash could be carried out to assess possibilities for further reduction of these impacts. It should be noted that the Japan Fiberboard and Particleboard Manufacturers Association assessed the levels of heavy metals in wood-based board (PB: 12 samples; MDF: 6 samples; IB: 2 samples) in 2016, and the levels of chromium VI were below the detection limit (5 mg/kg) (Japan Fiberboard and Particleboard Manufacturers Association 2016).

4.2 Comparison with other studies (cradle-to-gate)

We compared this study with other studies, which showed compositions of characterization results. The characterization results of PB showed similar compositions of PB produced in Brazil (Silva et al. 2014) and Iran (Kouchaki-Penchah et al. 2016) since most of the impacts were induced by utilities and adhesives. Kinds of utilities, however, were different. Regarding abiotic resource depletion, for example, significant impacts were diesel oil and heavy oil in Brazil (Silva et al. 2014) and natural gas in Iran (Kouchaki-Penchah et al. 2016) but electricity in this study.

As with the case of PB, utilities and adhesives were identified as hotspots of MDF produced in Brazil (Silva et al. 2013) and Iran (Kouchaki-Penchah et al. 2015). Regarding ecotoxicity, however, glyphosate herbicide showed the largest impact in MDF produced in Brazil (Silva et al. 2013) while adhesives were the largest in this study. In Japan, 76% of wooden material was covered by recycled wood (Table 4). On the other hand, 95% were provided with logs from forest in Brazil (Silva et al. 2013). Therefore, the difference in the hotspot was caused by the different wood material sources in Japan and Brazil.

The results of HB also displayed utilities and adhesives were hotspots, and these were the same with the case in Europe (González-García et al. 2009) though heat sources were different.

4.3 Formaldehyde impact in the use stage

The life time assumed in this study was 40 years to conform to that of Chaudhary and Hellweg (2014). In Japan, the average age of a demolished residential building has been estimated as 32.1 years (Ministry of Land Infrastructure Transport and Tourism 2016); thus, there was a possibility of overestimating the impact of the use stage.

While we demonstrated the substantial reduction of formaldehyde emissions during the use stage, the results made the relative impacts of the production stage stand out. The remaining impacts mainly left in the production stage may incur discussions regarding further regulations; however, the priority could be low for the following reasons. First, the magnitude of emissions from wood-based boards is small. The amount of formaldehyde emissions from lumber-wood products manufacturing industry was 39 t/year, and that from adhesives in furniture used in households was 143 kg/year in 2015 (Ministry of the Environment Japan 2016). The total amount of formaldehyde emission in Japan was 5826 t/year including 5094 t/year from mobile entities, such as diesel cars (Ministry of the Environment Japan 2016). These figures indicate the small contribution of wood-based products to formaldehyde emissions. Second, the regulations for the workplace environment have already been in place so that formaldehyde emissions are controlled during the production stage. However, the discussion above should not be generalized since LCA approaches on a relative basis, and the determination of whether impacts exceed thresholds of human health or not is beyond the function of LCA (ISO 2006).

In Japan, the Building Standards Law has required using lower-formaldehyde products since 2003. Similar regulations on formaldehyde emissions have also been introduced in other countries and regions, such as the USA and Europe (Ruffing et al. 2011; Salem and Böhm 2013). For example, the California Air Resources Board Phase 2 emission standard (CARB-P2) in California, USA, requires formaldehyde levels of less than 0.09 mg/m^3 for PB and 0.11 mg/m^3 for MDF. CARB-P2 for PB and MDF was enacted in 2011, and selling of products that do not satisfy the criteria is prohibited in California. In Europe, the European Union Green Public Procurement (EU GPP) criteria require wall panels to conform to the E1 standard (less than 0.13 mg/m^3). Austria, the Czech Republic, Denmark, Germany, Italy, and Sweden introduced mandatory requirements for wood-based boards to meet the E1 standard, and further strict criteria for the EU GPP have been discussed (Donatello et al. 2015).

These regulations are not easily comparable with each other because different test methods are adopted to quantify formaldehyde emissions from wood-based boards. The test method according to the regulation in California is a chamber method standardized in ASTM E1333-96 (ASTM International 2002), whereas a desiccator method (JIS A 1460; Japanese Standards Association 2001) is used in Japan. Furthermore, a perforator method (EN 120; The British Standard 2015) is utilized in Europe. However, the Japanese F-3 stars and F-4 stars grades correspond to values of approximately 0.07 and 0.04 mg/m^3 in ASTM E1333-96, respectively (Ruffing et al. 2011).

Similarly, the E1 standard in Europe corresponds to 0.14 mg/m^3 (PB) and 0.10 mg/m^3 (MDF) in ASTM 1333-96 (Ruffing et al. 2011).

Therefore, F-4 stars products, which dominate the Japanese market (Fig. 3), exhibit the lowest formaldehyde emissions in the use stage of the products in these major countries and regions; however, the regulations in other countries and regions have been tightened and formaldehyde emissions in the use stage have correspondingly fallen. Therefore, the significance of human health impacts in the production stage has been increased in countries that have introduced strict regulations on formaldehyde emissions.

4.4 Uncertainty analysis: modeling of formaldehyde emissions in the use stage

In the actual environment, FE values are influenced by temperature and humidity. Seasonal changes of FE were not negligible, as FE can increase to almost the initial value in the summer 1 year after installation (Hara et al. 2007; Liang et al. 2015). In addition, the model used for this study included certain uncertainties. Therefore, a case without decreasing FE in the life cycle was evaluated as an uncertainty analysis. If the FE of each grade of the regulation were maintained for 40 years, the total formaldehyde emissions were 5.26×10^{-2} kg/m^2 (F-1 star), 2.45×10^{-2} kg/m^2 (F-2 stars), 4.38×10^{-3} kg/m^2 (F-3 stars), and 1.40×10^{-3} kg/m^2 (F-4 stars). This result demonstrates that the contribution of the production stage in terms of impacts on human health was still significant for the F-4 stars products (Fig. 7). The uncertainty analysis overestimated emissions of formaldehyde in the use stage; however, the analysis confirmed that the impact of the production stage was significant for F-4 stars products. Therefore, we recommend preferentially improving the environmental performance of the production process of wood-based boards in countries with strict regulations on formaldehyde emissions.

4.5 Sensitivity analysis: impact of ventilation and other parameters

This study adopted the USEtox 2.01 model for evaluating the human health impacts induced by indoor emissions. The ventilation rate was an important parameter in establishing the characterization factors of USEtox 2.01 (Rosenbaum et al. 2015). This study adopted the factor of Organization for Economic Co-operation and Development (OECD) countries (0.64/h). In Japan, Mihara et al. (2004) surveyed the ventilation rates of 34 houses and obtained an average value of 0.59/h, while the Building Standards Law requires a level of more than 0.5/h for living rooms. Thus, a proportion of the human health impacts may be larger than the result obtained in this study if a living room is designed for the lowest level

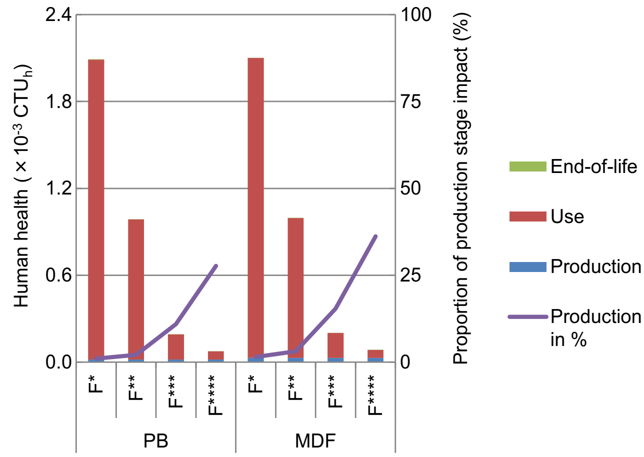


Fig. 7 Results of the uncertainty analysis: cradle-to-grave assessment of impacts to human health (total cancer and non-cancer impacts) if formaldehyde emission rates did not change over 40 years

prescribed by regulations. Salthammer et al. (2010) clarified that FE from building materials had fallen from 1996 to 2006, but this positive effect was canceled out by decreasing ventilation rates. Therefore, considering the impact of the use stage is still important in houses with high air-tightness and low ventilation rate. Furthermore, Rosenbaum et al. (2015) clarified that building occupation was also an important parameter. Therefore, the sensitivity of ventilation rate and number of people in the building was analyzed for an F-4 stars product of PB (Fig. 8). Both these parameters influenced the results; however, the production stage was significant in all cases.

Other parameters, such as building volume and amount of time people spend at home per day, also contribute variability to the characterization factors. The variability of these parameters can be as much as two orders of magnitude (Rosenbaum et al. 2015); therefore, their impacts in the use stage cannot be ignored.

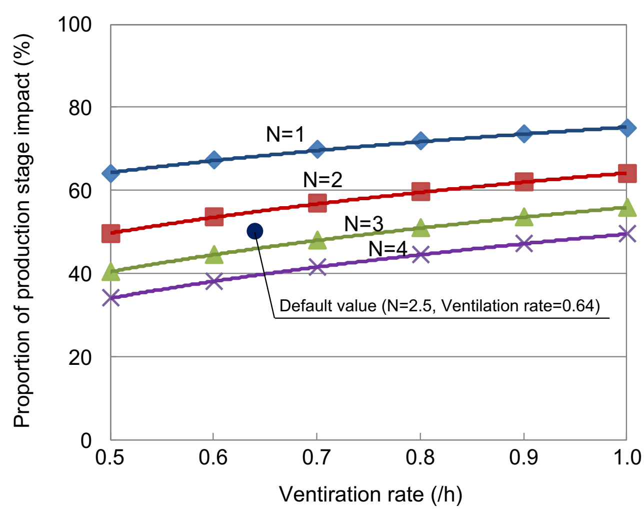


Fig. 8 Results of the sensitivity analysis: changes in the number of people in the building (N) and ventilation rate. Human health impact (total cancer and non-cancer impacts) of an F-4 stars PB product

5 Conclusions and recommendations

Generic LCA data of Japanese wood-based board (PB, HB, MDF, and IB) production (cradle-to-gate) were calculated. As an example, the greenhouse gas emissions for PB, HB, MDF, and IB production were 4.44×10^2, 3.31×10^2, 8.50×10^2, and 2.35×10^2 kg-CO_2 eq/m^3, respectively. Adhesives were significant for PB and MDF; utility supply was important for HB and IB. Zinc emitted to the atmosphere from wood boilers and chromium VI in discharged water from landfilled wood ash were the largest factors affecting the results for human health and ecotoxicity in HB and IB. Current wood boiler operations satisfy the relevant laws and several producers have already measured these substances; however, additional research on quantitative elemental analysis of wood fuel and incinerated ash could contribute to a further reduction of these impacts.

Life cycle (cradle-to-grave) assessment of PB and MDF revealed that shifting from F-1 star to F-4 stars products decreased impacts to human health (total of cancer and non-cancer effects) dramatically. Approximately 90% of human health impacts occurred in the use stage for the F-1 star and F-2 stars products. In contrast, for the F-4 stars products, which occupy the largest share of production in Japan, the production stage accounted for more than half of the impacts owing to reductions in formaldehyde emissions in the use stage. Regulations on formaldehyde emissions in the use stage in other places (e.g., USA and Europe) are not as strict as those in Japan; however, regulations in other countries and regions have also been tightened and formaldehyde emissions during the use stage have fallen. The significance of human health impacts from the production stage has been relatively increased in countries and regions that have introduced strict regulations on formaldehyde emission. Therefore, we recommend preferentially improving the environmental performance of the production process of wood-based boards in countries with strict regulations on formaldehyde emissions.

Acknowledgements The production data of wood-based boards were collected by the life cycle assessment committee for wood-based boards comprising member companies in Japan Fiberboard and Particleboard Manufacturers Association and Tokyo University of Agriculture and Technology. The authors thank the companies (10 factories of 7 companies) who contributed to the data collection. The authors also thank Satoshi Terashima and Hiroki Tsujimoto who contributed to the data reduction while pursuing their master's degree at the Tokyo University of Agriculture and Technology. This study was partly supported by the Forestry Agency and the Ministry of Environment of Japan.

References

ASTM International (2002) ASTM E1333–96: standard test method for determining formaldehyde concentrations in air and emission rates from wood products using a large chamber. ASTM International, West Conshohocken

Brown SK (1999) Chamber assessment of formaldehyde and VOC emissions from wood-based panels. Indoor Air 9:209–215

Chaudhary A, Hellweg S (2014) Including indoor offgassed emissions in the life cycle inventories of wood products. Environ Sci Technol 48: 14607–14614

Donatello S, Moons H, Wolf O (2015) Revision of green public procurement criteria for furniture. Seville

Ekvall T, Tillman A-M (1997) Open-loop recycling: criteria for allocation procedures. Int J Life Cycle Assess 2:155–162

González-García S, Feijoo G, Widsten P et al (2009) Environmental performance assessment of hardboard manufacture. Int J Life Cycle Assess 14:456–466

Guinée JB, Gorrée M, Heijungs R et al (2002) Life cycle assessment: an operational guide to the ISO standards. I: LCA in perspective. IIa: guide. IIb: operational annex. III: scientific background. Kluwer Academic Publishers, Dordrecht

Hara K, Mori M, Ishitake T et al (2007) Changes volatile in the airborne concentrations of formaldehyde and organic compounds in an elementary schoolroom over two years after renovation. J Soc Indoor Environ Japan 9:97–103

Hauschild MZ, Huijbregts M, Jolliet O et al (2008) Building a model based on scientific consensus for life cycle impact assessment of chemicals: the search for harmony and parsimony. Environ Sci Technol 42:7032–7037

Hauschild MZ, Goedkoop M, Guinée J et al (2013) Identifying best existing practice for characterization modeling in life cycle impact assessment. Int J Life Cycle Assess 18:683–697

Hellweg S, Demou E, Bruzzi R et al (2009) Integrating human indoor air pollutant exposure within life cycle impact assessment. Environ Sci Technol 43:1670–1679

Huijbregts MAJ, Rombouts LJA, Ragas AMJ, van de Meent D (2005) Human-toxicological effect and damage factors of carcinogenic and noncarcinogenic chemicals for life cycle impact assessment human-toxicological effect and damage factors of carcinogenic and noncarcinogenic chemicals for life cycle impact assessment. Integr Environ Assess Manag 1:181–244

International Agency For Research on Cancer (2012) Formaldehyde

Iritani DR, Silva DAL, Saavedra YMB et al (2015) Sustainable strategies analysis through life cycle assessment: a case study in a furniture industry. J Clean Prod 96:308–318

ISO (2006) ISO 14040. environmental management—life cycle assessment—principles and framework. International Organization for Standardization, Geneva

Itsubo N, Inaba A (2014) Indoor air pollution, LIME2: life-cycle impact assessment method based on endpoint modeling. In: JLCA Newsletter No.17. LCA Society of Japan, Tokyo, Japan, p 65–105

Japan Fiberboard and Particleboard Manufacturers Association (2016) Internal servey

Japanese Standards Association (2001) JIS a 1460: building boards determination of formaldehyde emission—desiccator method. Japanese Standards Association, Tokyo

Japanese Standards Association (2014) JIS a 5905: fiberboards. Japanese Standards Association, Tokyo

Japanese Standards Association (2015) JIS a 5908: particleboards. Japanese Standards Association, Tokyo

Kofujita H, Watanabe H, Sera K, Futatsugawa S (2005) Determination of inorganic trace elements in wood materials by PIXE method. Bull Iwate Univ For 39–45

Kouchaki-Penchah H, Sharifi M, Mousazadeh H, Zarea-Hosseinabadi H (2015) Life cycle assessment of medium-density fiberboard manufacturing process in I. R. Iran. J Clean Prod 112:351–358

Kouchaki-Penchah H, Sharifi M, Mousazadeh H, Zarea-Hosseinabadi H (2016) Gate to gate life cycle assessment of flat pressed particleboard production in I. R. Iran. J Clean Prod 112(Part 1):343–350

Liang W, Yang S, Yang X (2015) Long-term formaldehyde emissions from medium-density fiberboard in a full-scale experimental room: emission characteristics and the effects of temperature and humidity. Environ Sci Technol 49:10349–10356

McDevitt JE, Grigsby WJ (2014) Life cycle assessment of bio- and petrochemical adhesives used in fiberboard production. J Polym Environ 22:537–544

Mihara K, Yoshino H, Mitamura T et al (2004) Measurement of ventilation rates in occupied 34 houses. J RIEMAM 52:166–169

Ministry of Economy Trade and Industry (2016) Yearbook of current production statistics mineral resources and petroleum products, ceramics and building materials 2013. Tokyo, Japan

Ministry of Land Infrastructure Transport and Tourism (2016) Housing economy data. In: Minist. Land, Infrastructure, Transp. Tour. http://www.mlit.go.jp/statistics/details/t-jutaku-2_tk_000002.html. Accessed 18 Mar 2016

Ministry of the Environment Japan (2016) PRTR information plaza. http://www.env.go.jp/en/chemi/prtr/prtr.html. Accessed 22 Apr 2016

Myhre G, Shindell D, Bréon F-M et al (2013) Anthropogenic and natural radiative forcing. In: Climate Change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

Rivela B, Hospido A, Moreira T, Feijoo G (2006) Life cycle inventory of particleboard: a case study in the wood sector. Int J Life Cycle Assess 11:106–113

Rivela B, Moreira MT, Feijoo G (2007) Life cycle inventory of medium density fibreboard. Int J Life Cycle Assess 12:143–150

Rosenbaum RK, Bachmann TM, Gold LS et al (2008) USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int J Life Cycle Assess 13:532–546

Rosenbaum RK, Meijer A, Demou E et al (2015) Indoor air pollutant exposure for life cycle assessment: regional health impact factors for households. Environ Sci Technol 49:12823–12831

Ruffing TC, Shi W, Brown NR, Smith PM (2011) Review of United States and international formaldehyde emission regulations for interior wood composite panels. Wood Fiber Sci J Soc Wood Sci Technol 43:21–31

Salem MZM, Böhm M (2013) Understanding of formaldehyde emissions from solid wood: an overview. Bioresources 8:4775–4790

Salthammer T, Mentese S, Marutzky R (2010) Formaldehyde in the indoor environment. Chem Rev 110:2536–2572

Santos MFN, Battistelle RAG, Bezerra BS, Varum HS (2014) Comparative study of the life cycle assessment of particleboards made of residues from sugarcane bagasse (Saccharum spp.) and pine wood shavings (*Pinus elliottii*). J Clean Prod 64:345–355

Saravia-Cortez AM, Herva M, García-Diéguez C, Roca E (2013) Assessing environmental sustainability of particleboard production process by ecological footprint. J Clean Prod 52:301–308

Sawada Y, Ando K, Hattori N, Tamura Y (2006) Inventory analysis of adhesives used for wood based materials. Mokuzai Gakkaishi 52: 235–240

Silva DAL, Lahr FAR, Garcia RP et al (2013) Life cycle assessment of medium density particleboard (MDP) produced in Brazil. Int J Life Cycle Assess 18:1404–1411

Silva DAL, Lahr FAR, Pavan ALR et al (2014) Do wood-based panels made with agro-industrial residues provide environmentally benign alternatives? An LCA case study of sugarcane bagasse addition to particle board manufacturing. Int J Life Cycle Assess 1767–1778

Silva DAL, Lahr FAR, Varanda LD et al (2015) Environmental performance assessment of the melamine-urea-formaldehyde (MUF) resin manufacture: a case study in Brazil. J Clean Prod 96:299–307

Skaar C, Jørgensen RB (2013) Integrating human health impact from indoor emissions into an LCA: a case study evaluating the significance of the use stage. Int J Life Cycle Assess 18:636–646

Steubing B, Wernet G, Reinhard J et al (2016) The ecoinvent database version 3 (part II): analyzing LCA results and comparison to version 2. Int J Life Cycle Assess 21(9):1269–1281

Tahara K, Onoye T, Kobayashi K et al (2010) Development of inventory database for environmental analysis(IDEA). In: Proceedings of the 9th International Conference on Ecobalance. Tokyo, p 119

The British Standard (2015) BS EN ISO 12460–5:2015: wood-based panels. Determination of formaldehyde release. Extraction method (called the perforator method). BSI, London

Wernet G, Bauer C, Steubing B et al (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21(9):1–13

Wilson J (2010) Life-cycle inventory of medium density fiberboard in terms of resources, emissions, energy and carbon. Wood Fiber Sci 42:107–124

Zinn TW, Cline D, Lehmann WF (1990) Long-term study of formaldehyde emission decay from particleboard. For Prod J 40:15–18