Original Research

Life Cycle Assessment and Eco-Efficiency of Para-Rubber Wood Production in Thailand

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Received: January 3, 2014
Accepted: January 20, 2015

Abstract

Thailand is currently the world's leader in para-rubber wood furniture exports, contributing revenue to the country of more than $1 billion US annually. However, the life cycle of para-rubber wood production causes environmental impact in multiple ways. This research aims to investigate the environmental impact and eco-efficiency of the para-rubber wood industry. The life cycle inventory of such is gathered from more than 60% of the entire para-rubber cultivation areas in Thailand, which can be considered as the national database. Five gate-to-gate procedures are included in this assessment, namely plantation, felling, mill saw, finger joint, and lamination. The life cycle impacts of 15 products are assessed on a cradle-to-gate basis with SimaPro 7.3.2 applied to characterize five impact categories, including global warming potential, abiotic depletion potential, acidification potential, eutrophication potential, and ozone depletion potential. The eco-efficiency level of each process is calculated and compared. According to this study, emission sources of the industry can be pointed to the activities in each life cycle step: direct emission, fertilizer production, chemical production, biomass fuel production, fossil fuel production, transport fuel production, and electricity. As a result, plantations exhibit the most eco-efficiency while the mill saw is the step that possesses the highest potential to be enhanced to the highest eco-efficiency. A potential to move onto a higher level in terms of felling and the finger-joint process is virtually impossible.

Keywords: para-rubber wood, environmental management, LCI, LCIA, eco-efficiency

Introduction

Globalization and population concentrations in urban areas in concomitance with modernization of lifestyle have driven the deforestation and degradation of natural forests globally. Industrial forest plantations satisfy one-third of global wood demands [1], but it is not widely known that timber from non-forest plantations has gradually become a significant wood resource in recent years [2, 3]. The emergence of non-forest wood resources could be a consequence of both strict logging control in natural forests and continuous improvements of wood processing technology for non-forest plantations. Para-rubber (*Hevea brasiliensis*) is one of the essential non-forest raw materials, which has already replaced forest plantation wood in various end products in several regions, especially in Southeast Asia. Thailand is now one of the world's leaders in para-rubber wood furniture exports [4]. In 2003 total gross export value of kiln-dried rough sawn para-wood and its products was $1.58 billion US (Thai Baht: 30 THB ≈ 1 USD). This increased to more than $3 billion US by 2008, around 70% of which was from various kinds of finished furniture and components. These exclude domestic use, with an estimated value of almost 700 million US annually. Even though the

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forecast of Thailand potential sawn wood availability was projected to increase, such an expected amount was usually underestimated (i.e., from 2.8 million m^3 to 4.18 million m^3 in 1997, and from 0.84 million m^3 to 1.25 million m^3 in 2012).

However, the disadvantages hindering its environmentally friendly quality are also evident in para-rubber wood. First of all, timber recovery is low at about 15-35% in small sawmills and only about 25% on average. Moreover, it biodegrades rapidly and is susceptible to insect infestations after felling. Para-rubber wood logs must be sawn as quickly as possible and preserved with chemicals. Then, kiln-dry processing after preservation – consuming a massive amount of energy – is required. Finally, kiln-dry rough sawn para-rubber wood is not well-liked for use as a final product. Consequently, an inevitable processing for further products as wood joint and laminated wood tends to increase energy consumption and additional waste.

A variety of tools have been utilized to analyze the environmental impacts of different systems [5]. The life cycle assessment (LCA) is a frequently-used and comprehensive tool for the development control of technical activities or the environmental impact evaluation of products or services. Its scope is the entire life cycle of a product, from the extraction of raw materials to manufacturing, use, and end of life [6]. Furthermore, eco-design or design for the environment (DfE) is a concept that integrates multifaceted aspects of design and environmental considerations [7]. The definition of sustainable solutions for products or services is based on the minimization of negative consequences under economic, environmental, and social points of views, throughout and beyond the life-cycle of products [8]. To date, only one study combining LCA and DfE for wood-based products is available in the literature [9], as well as for innovation-driven companies [10]. From a literature review, none of the previous research has conducted an analysis of para-rubber wood and its downstream products.

In this project, LCA is used to develop life cycle inventory (LCI) and life cycle impact assessment (LCIA) of eight products: para-rubber, wood logs, twig and branch, slab, sawdust, kiln-dried timber, finger joint, and laminated wood. Five impact categories for this research are global warming potential (GWP), ozone depletion (ODP), acidification potential (AP), eutrophication potential (EP), and abiotic depletion potential (ADP). These results will be useful for downstream industries, especially for the construction sector, serving as comprehensive data for environmental management. In addition to product impact assessment, this research also conducted the impact assessment of each process: plantation, felling, mill saw, finger joint, and lamination, herewith identifying emission sources for every impact category. This will bring improvement to production processing and drive it to be more environmentally friendly. Furthermore, environmental economics will be studied by using the concept of eco-efficiency (EE), which will be used as a guideline to determine whether the process should be developed in economic or environmental perspectives, for sustainable development balance between environment conservation and economic value added.

Methodology

Scope and Boundary

This research was developed in compliance with the international standards of series 14040 and 14044 [11, 12]. The cradle-to-gate life cycle boundary presented in Fig. 1 is an integration of gate-to-gate procedure, including plantation, felling, mill saw, finger joint and lamination. Within the boundary of this life cycle, there are cradle-to-gate assessments for certain products, including: flesh latex, para-rubber wood, rubber residue, wood logs, branch, slab, kiln-dried timber AB and C, finger joint AB and C, laminate AB and C, and sawdust. Definition and specification of kiln-dried para-rubber wood is described in Table 1.

Life Cycle Inventory

Life cycle inventory of plantation phase is established by collecting data from 1,137,646.08 hectares – 63% of

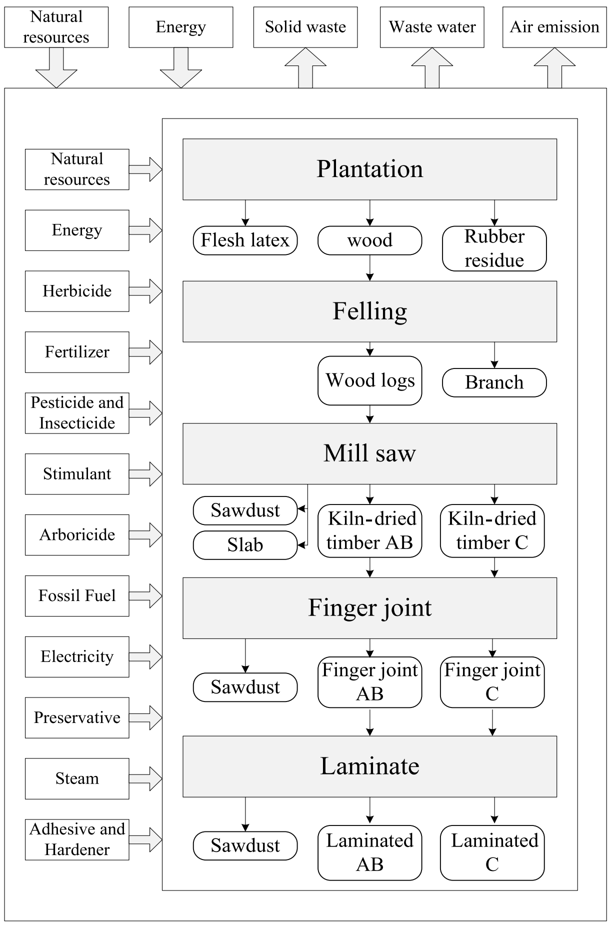
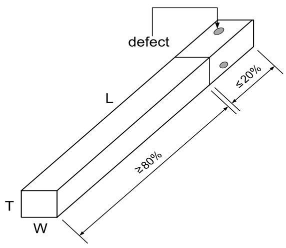
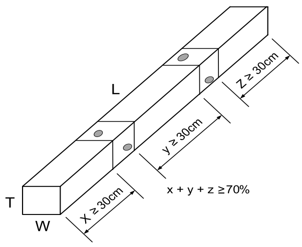
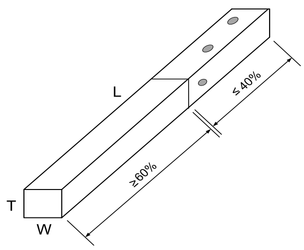


Fig. 1. Scope and boundary of study.

Table 1. Definition and specification of kiln-dried para-rubber wood timber.

<table>
<tr><td rowspan="2">Category of rubber wood</td><td colspan="3">Quality and characteristics for grabe of rough sawn timber rubber wood</td></tr>
<tr><td>A</td><td>B</td><td>C*</td></tr>
<tr><td>Thickness</td><td colspan="3">1/2"; 6/8"; 1"; 1.1/4"; 1.1/2"; 2"; 2.1/2"; 3"; 4"</td></tr>
<tr><td>Width</td><td colspan="3">2"; 3"; 4"</td></tr>
<tr><td>Length</td><td colspan="3">1.00 m; 1.20 m; 1.30 m; 1.50 m</td></tr>
<tr><td>Special size</td><td colspan="3">Other than sizes of which are not mentioned above of the rough sawn timber rubber wood is considered as special size</td></tr>
<tr><td>Size allowance</td><td colspan="3">Additional allowance for the thickness & widthness is not less than 2 mm and for the length is not less than 3 cm (or 30 mm)</td></tr>
<tr><td>Description and specifications of rough sawn timber rubber wood</td><td>a. For those selected rough sawn timber rubber wood after defects selection & the maximum length shall be more than or equal to 80% (provided 4 sides is clear) of the wood length as per sizes mentioned above.

</td><td>a. For those selected rough sawn timber rubber wood after defects selection & the minimum length shall be more than 30cm after cutting & add up shall be more than 70% of the wood length as per sizes mentioned above.


b. For those selected rough sawn timber rubber wood after defects selection & the minimum length after cutting shall be more than 60% of the wood length as per sizes mentioned above

</td><td>a. The mixing ratio grade of selected kiln-dried rough sawn timber rubber wood after defects selection as described under the Thai Parawood Association specification for grade (A:B) is 40:60

Remark

– Timber is kiln - dried rough sawn timber after has gone through the chemical threatment process
– 4 side clear is 4 sides of the wood without any defects BUT the defects which is less than or equal to 5 mm
– Defects is black knots, cracks, black lines, bad fungus, blue stains, bucks and any holes found on timber</td></tr>
<tr><td>Moisture content</td><td colspan="3">Maximum 12%</td></tr>
</table>

* Any rough saw timber which their spacification disqualified as grade A, B and AB, they will be classified as grade C

the entire para-rubber cultivation areas in Thailand in 2008. Selected areas are located in 10 provinces with high productivity, from southern (84%), eastern (13%), northeastern (1.8%), and northern (0.4%). Thirty mill saw manufacturers, accounting for 63% of all product in Thailand in 2008, represent data for the felling and mill saw phases. For downstream products, finger joint and laminated, collected data of six manufacturers from southern Thailand are represented. This array of data accounts for 62% of all Thai product.

The eco-profile of all products is scrutinized, including indirect environmental impact related to energy source generation, water, and raw material supply. The reference flow of each product is 1 kilogram, of which the environmental loads are allocated by mass. The list of input materials shown in Fig. 1 is materials with significant environmental impact normally detected in the process. Energy and natural resources are consumed both during production and also in some processes, resulting in emissions and pollution problems such as air pollution and hazardous wastes. As for mobile agriculture machinery like tractors, reapers, etc., in cases where the substances emitted to the receiving environment are not fully monitored, this assessment can be estimated by the following equation:

$$AE = AF \times F \quad (1)$$

AE = Amount of emission
AF = Amount of fuel
F = Factor of substances emission (depends on fuel type)

For carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), factors of emission are obtained from the 2006 IPCC Guidelines, Vol. 2 Energy [13]. Factors from the 2009 EMEP/EEA air pollutant emissions inventory guidebook, non-road mobile sources, and machinery are used for carbon monoxide (CO), non-methane volatile organic compound (NMVOC), nitrogen oxide (NO_x), and particulate matter (PM_{10}) [14]. For SO_2, 0.035% by weight is used to calculate the factor, with the value of the maximum sulfur allowed by Department of Energy Business Thailand to be composed in fuels such as gasoline and diesel. In the case of stationary machines, the same equation can be applied. 2006 IPCC Guidelines also are used for factors of CO_2, CH_4, and N_2O. Factors of other released gases apart from the greenhouse ones are obtained from the 2009 EMEP/EEA air pollutant emissions inventory guidebook.

The amount of nitrogen (N) and phosphoric anhydride (P_2O_5) in organic fertilizer can be estimated by literature [15, 16], while nitrogen, phosphoric anhydride, and potassium oxide (K_2O) for *d* kg of chemical fertilizer *a-y-c* are estimated by the following equation.

$$N \text{ (kg)} = (a \times d)/100 \quad (2)$$

$$P_2O_5 \text{ (kg)} = (y \times d)/100 \quad (3)$$

$$K_2O \text{ (kg)} = (c \times d)/100 \quad (4)$$

… where *a, y*, and *c* are percentages of N, P_2O_5, and K_2O contained in fertilizer. Nitrous oxide (N_2O) emissions as a result of any N-contained fertilizer use is [17]:

$$N_2O \text{ (kg)} = \text{weight of nitrogen (kg)} \times (44/28) \times (1/100) \quad (5)$$

Limestone consisted of carbon such as calcic limestone ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) when dissolved in water, when bicarbonate is formed and finally results in CO_2 emissions. Evaluation of CO_2 from this phenomenon is:

$$CO_2 \text{ (kg)} = [(CaCO_3 \text{ (kg)} \times 0.12) + (CaMg(CO_3)_2 \text{ (kg)} \times 0.13)] \times (44/12) \quad (6)$$

CO_2 emission from urea ($CO(NH_2)_2$) is estimated based on the assumption that all carbon in urea will alter to CO_2, so:

$$CO_2 \text{ (kg)} = CO(NH_2)_2 \text{ (kg)} \times 0.2 \times (44/12) \quad (7)$$

Nitrogen oxide (NO_x) from fertilizer use can be evaluated on the grounds of the assumption that 21% of N_2O transforms to NO_x [18].

$$NO_x \text{ (kg)} = 0.21 \times N_2O \text{ (kg)} \quad (8)$$

Total amount of nitrogen leaching and runoff to underground and surface water can be approximated by using the relationship of Nevison [19].

$$N \text{ (kg-year}^{-1}) = (NFert + NEX) \times FRACleach \quad (9)$$

NFert = weight of N in all fertilizer (kg-year^{-1})
NEX = weight of N in animal manure (kg-year^{-1})
FRACleach = partitioning factor (0.2 in case of a combination with organic fertilizer, 0.3 if otherwise)

Phosphorus leaching into the underground water is not taken into account, since almost all phosphorus is absorbed by soil particles before reaching the underground source [20, 21]. Runoff phosphorus can be considered by [18]:

$$P \text{ (kg-ha}^{-1}\text{-year}^{-1}) = P_{average} \times F_{runoff} \quad (10)$$

$$F_{runoff} = [(0.2/80) \times P_2O_{5min}] + [(0.7/80) \times P_2O_{5sl}] + [(0.4/80) \times P_2O_{5man}] \quad (11)$$

$P_{average}$ = average runoff (kg-ha^{-1}-year^{-1}) depends on type of land use
0.715 (kg-ha^{-1}-year^{-1}) for arable land
0.25 (kg-ha^{-1}-year^{-1}) for intensive permanent pastures and meadows
0.15 (kg-ha^{-1}-year^{-1}) for extensive permanent pastures and meadows
F_{runoff} = correction factor
P_2O_{5min} = amount of P_2O_5 in mineral fertilizer (kg-ha^{-1}-year^{-1})
P_2O_{5sl} = amount of P_2O_5 in slurry of liquid sewage sludge (kg-ha^{-1}-year^{-1})
P_2O_{5man} = amount of P_2O_5 in solid manure (kg-ha^{-1}-year^{-1})

Impact Assessment

The quantified inventory data was analyzed using SimaPro 7.3.2 software. The IPCC 2007 (Intergovernmental Panel on Climate Change) impact assessment method was chosen for this analysis and the results for global warming aspect and CML 2 baseline 2000 (Center of Environmental Science of Leiden University) was chosen among those potentials of abiotic depletion, acidification, eutrophication, and ozone depletion. Para-rubber wood final products contain some chemicals that may be released in the end of the product phase, although emissions from this phase were not included in this calculation because it was considered insignificant.

Moreover, carbon dioxide absorbed and locked in living trees, aboveground biomass, underground biomass, soil organic carbon, durable constructions, and furniture were excluded from GHG balance.

Normalization, Weighting, and Eco-Efficiency

Usually, the normalization step is widely implemented in LCA of product in order to understand the significance of the impact categories better, but in this study normalization is applied to determine which process is environmentally friendly. In this case, normalization references (NRs) of each impact category are summarized by all impact scores in each production stage. Normalized scores of every category were summarized using equal weighting, to be a single score for each production stage. To evaluate eco-efficiency, values added (in USD) of each stage were divided by their own single score (or multiplied by inverse of their single score). Then the single score impact and value added were plotted on a logarithmic scale to define the direction to sustainable development.

Process Definition

Plantation

In detail, the plantation phase consists of several processes that affect the environment. Land preparation for seeding – including ploughing and leveling of soil – can generate small particle matter. Preliminary treatments and use of pesticides and herbicides also leave their residues in the natural environment. Successively, organic manure and chemical fertilizers applied into water solutions are added to enrich the soil and are occasionally leached into the natural water resource. Diseases and pests are problems that decrease not only rubber-wood growth rate but also both latex quality and quantity or even kill the tree. The rubber plants grown in Thailand are susceptible to several diseases, most of which are caused by fungi. Diseases can be classified from the different parts of the rubber trees that are destroyed, including leaf, stem-branch, and root diseases. Therefore, many chemicals are applied on rubber trees with an aim to control pests and diseases. To uphold the highest efficiency of latex production while maintaining stable growth and development of rubber in the tapping season, stimulants are commonly used [22, 23]. 2-Chloroethylphosphonic acid (Ethephon) is one kind of growth regulator group for plants and it is applied to stimulate blooming of some plants.

Felling

There are two methods for felling rubber trees in Thailand. The first widely used around Thailand is by felling a trunk with a chainsaw and then delimbing it. After the felling, the landowner can remove the stumps by two methods, either through chemical treatment or by using tractors to uproot them. The second is mainly used in southern Thailand by felling an entire tree, including the root system, with a bulldozer and subsequently cutting and delimbing the trunk. The stumps are either burnt at the plantation site or used later as fuel wood [24].

Mill Saw

Timber recovery is another dilemma holding back the development of the para-rubber wood industry due to its low yield. The normal sawmill production line usually consists of transport of logs, primarily sawing with a headrig bandsaw with a carriage, then secondary cutting of cant and flitch with a small bandsaw. From a previous study, para-rubber wood timber recovery is rated at an average of 25%, the remainder being wood slab 50% and saw dust 25%. The timber should be treated by the pressure or diffusion process promptly after it is cut to protect against stain, fungi, and insects. Some cuts of para-rubber wood may have lighter or darker shades than others. Those defects can be avoided by bleaching the wood or using a bleaching toner on the wood together with preservation agents. The keys to fungus stain or decay on para-rubber wood prevention rely not only on chemical treatment but also on immediate drying so that the moisture content reaches a low level to destroy the living conditions of fungus. Kiln-drying consumes a massive amount of energy. Many researchers report that 40-80% of energies used in para-rubber wood processing are attributed to the kiln-drying procedure to minimize the moisture content of timber.

Finger Joint and Lamination

The process starts with cutting vertically down about 25-36 cm to minimize warping or bending. Then, slide to cut the surface to the desired thickness, and also its side to the required width. Graded and sorted para-rubber wood having the same shade of color then are connected by the finger joint technique, which has been developed because it is currently not possible to make strong butt joints by gluing the end grain of adjacent boards. In finger joints the glued surfaces are on the side grain rather than end grain, and the glue line is shear stressed rather than in tension. Normally in wood processing, the adhesives used are a two-composite mixture (adhesive and hardener) such as polyvinyl alcohol with isocyanate, polyvinyl acetate with chromium, or aluminium salt. Moreover, each glued area requires pressure of approximately 5-8 kg per cm^2 (0.5-0.6 MPa) and some heat to raise the temperature up to 60-70ºC.

Results and Discussion

Tables 2-6 are input-output data of each process in the para-rubber wood industry. All of the data are presented by year average, except the plantation process, because the obtained data evaluated by collecting information from one hectare average over lifetime period, seedling,

Table 2. Input-output data of the plantation process.

Plantation (per hectare)			
Input	Qty (kg)	Output	Qty (kg)
Sprout	903.42	Para-rubber wood	278,009.03
Diesel	207.36	Flesh latex	156,134.85
Lubricant oil	3.27	Rubber residue	3,806.72
N-fertilizer	743.51	Direct emission from fertilizer	
P_2O_5-fertilizer	295.97	N_2O	11.68
K_2O-fertilizer	762.44	NH_3	74.35
DAP	407.64	NMVOC	4.43E-06
Urea	1,621.55	NO_x	156.14
MOP	1,042.47	PM_{10}	1,159.87
48% Glyphosate	80.21	CO_2 (from urea)	1,189.13
100% Paraquat	77.60	N-leach	223.05
35% Metalaxyl	1.11	Prunoff	2.93
2.5% Ethephon	1.45	Direct emission from fuel	
		CO_2	465.60
		CH_4	0.03
		N2O	0.18
		CO	2.27
		NMVOC	0.70
		NO_x	7.27
		PM_{10}	0.36
		SO_x	7.26

Table 3. Input-output data of the felling process.

Felling (per year)			
Input	Qty (kg)	Output	Qty (kg)
Para-rubber wood	150,407,041.92	Wood logs	125,202,868.73
Diesel (transport)	257,525.19	Branch	25,204,173.19
Diesel (chain saw)	40,094.23	Direct emission from transportationr	
Lubricant oil	2,800.51	CO_2	578,230.77
		CH_4	32.38
		N_2O	223.18
		CO	2,817.07
		NMVOC	866.83
		NO_x	9,024.46
		PM_{10}	447.58
		SO_x	9,013.38
		Direct emission chain saw	
		CO_2	90,025.06
		CH_4	3.64
		N_2O	0.73
		CO	48.60
		NMVOC	12.15
		NO_x	121.49
		PM_{10}	26.12
		SO_x	170.09

and harvesting until production of flesh latex become uneconomical (25-30 years). On the left side of the table are input material and energy, normally derived from questionnaires from respondents associated in each process; rubber farmer, timber industry, etc. On the right side are product output, which also was obtained from questionnaires as well as emissions calculated in the 2006 IPCC and 2009 EMEP/EEA guidebooks. For the acquired LCI, it can be noticed that diesel is usually used in every process, but it has a different effect depending on how it is used. Diesel used as fuel can be classified into two types, in mobile and stationary machines as they cause different emissions. Furthermore, in some processes such as a mill saw, diesel is used as lubricant. Therefore, its impact is not via air emissions, but it turns out to be wasted after it is used. Water is another input that needs to be identified with the purpose of correct use.

Fig. 2 shows the percentage of wood utilization for one hectare para-rubber wood industry for a 25-year life cycle. Production of para-rubber wood, compared to flesh latex, is almost twice. However, timber recovery is another dilemma hampering development of this industry because of its low yield. This study shows that para-rubber wood timber is recovered approximately at 25% while the remainder, namely wood slab, branches, and twigs are 50% and sawdust 25%. In addition, the utilization of rubber wood depends on the rubber strains that have different maturation and latex yields. Normally, rubber farmers prefer good strains with higher latex yield, of which the size is typically smaller. Compared with the lumber recovery volume of fresh logs and sawed wood among four families, PB 235 provides the highest yield, since it has the topmost shape and fewer branches. On the other hand, RRIT 251 returns the least recovery ratio, because of its bush shape and many branches. In the case of BPM 24, it has a lot of defects from its knot; therefore its average lumber recovery ratio is low. About 88% of para-rubber wood logs are brought to kiln-dried timber industry, and the remainder is put up on other markets. Most kiln-dried timber is directly sold as raw material for furniture manufacturing and the remaining 15% is processed further for finger joints and then laminated. Wood slab takes place in this process, almost all of them are used as fuel to provide energy for timber drying process. Saw dust occur from three processes; kiln dried,

Table 4. Input-output data of the mill saw process.

Mill saw (per year)			
Input	Qty (kg)	Output	Qty (kg)
Wood logs	111,462,065.91	KD timber AB	44,584,826.36
Plastic paint	1,918.89	KD timber C	11,146,206.59
Diesel (as lubricant)	4,552.78	Saw dust	11,146,206.59
Diesel	21,829.57	Slab	44,584,826.36
Saw cutter	3,671.80	Ash	1,681.35
Boron	66,541.35	Evaporated water	276,505.05
$Ca(ClO)_2$	6,225.49	Direct emission from biomass	
Water (solvent)	8,838,795.53	CH_4	8,847.84
Water (Steam)	276,505.05	N_2O	1,179.71
Wood chips	15,600,744.86	Direct emission from transportation	
Saw dust	4,179,425.43	CO_2	49,014.74
Hydroguard	2,569.82	CH_4	1.98
Input	Qty (kWh)	N_2O	0.40
Electricity	1,475,755.52	CO	26.46
		NMVOC	6.61
		NO_x	66.15
		PM_{10}	14.22
		SO_x	92.61

KD = kiln-dried

Table 5. Input-output data of the finger joint process.

Finger joint (per year)			
Input	Qty (kg)	Output	Qty (kg)
KD timber (AB, C)	5,774,104.73	Finger joint AB	3,699,189.62
Lubricant oil	48.60	Finger joint C	411,021.07
Polyvinyacetate	47,922.02	Saw dust	1,663,894.04
Input	Qty (kWh)		
Electricity	1,211,221.45		

Table 6. Input-output data of the laminate process.

Laminate (per year)			
Input	Qty (kg)	Output	Qty (kg)
Finger joint AB	3,719,881.65	Laminated AB	3,719,881.65
Finger joint C	413,320.18	Laminated C	413,320.18
Lubricant oil	120.29	Saw dust	568,568.78
PS-butadiene	50,688.39	Used sand paper	1,046.80
Hardener	7,161.69	Direct emission from transportation	
Sand paper	1,046.80	CO_2	4,554.14
PE	4,012.39	CH_4	0.18
Crepe paper	16,163.21	N_2O	0.04
Diesel	2,028.27	CO	2.46
Input	Qty (kWh)	NMVOC	0.61
Electricity	801,462.67	NO_x	6.15
		PM_{10}	1.32
		SO_x	8.60

finger joint and laminated. Of all mentions, the kiln-dry process makes the most contribution.

From Table 7 for the five-year average price, it can be seen that the price of fresh latex per kilogram is the highest, while the price of para-rubber wood is much lower. The price of wood slab and saw dust are approximately comparable, since their values are assessed by implementation in the form of fuel.

Table 8 is the result of LCIA of 1 kg product before normalization. GWP is global warming potential in unit of kilogram carbon dioxide equivalent (kg CO_2-eq). ADP is abiotic depletion in unit of kilogram antimony equivalent (kg Sb-eq). AP is acidification in unit of kilogram sulfur dioxide equivalent (kg SO_2-eq). EP is eutrophication in unit of kilogram phosphate equivalent (kg PO_4-eq), and ODP is ozone layer depletion in unit of kilogram chlorofluorocarbon-11 (kg CFC-11-eq). This result is based on analysis using SimaPro 7.3.2 software with mass allocation obtained from mass balance as shown in Fig. 2. It is noticeable that in a product of the same procedure, when analyzed with mass allocation method, the impact assessment is similar and increases as the process progresses. Another remark is that even for the same product, such as saw dust that occurred in different stages, environmental impact is distinct because it is produced by a different process and also has different accumulated impacts from the previous step. The findings in this stage do not indicate which process has more contribution to environmental destruction, until the yield of each step is taken into account. From a literature review, some research can be used to compare these results, and none of them has the same scope and boundary. Furthermore, all literature mentioned here concerned only GWP. In one part of the research "Greenhouse emissions from rubber industry in Thailand," only the global warming potential of para-rubber plantations was reported [25]. However, environmental impact allocation to wood was not in its scope of study, therefore all of GWP impact was only the responsibility of flesh latex. In this literature, GWP is 0.203 kg CO_2-eq per kg of flesh latex, in which 0.116 kg CO_2-eq originated from production of raw materials

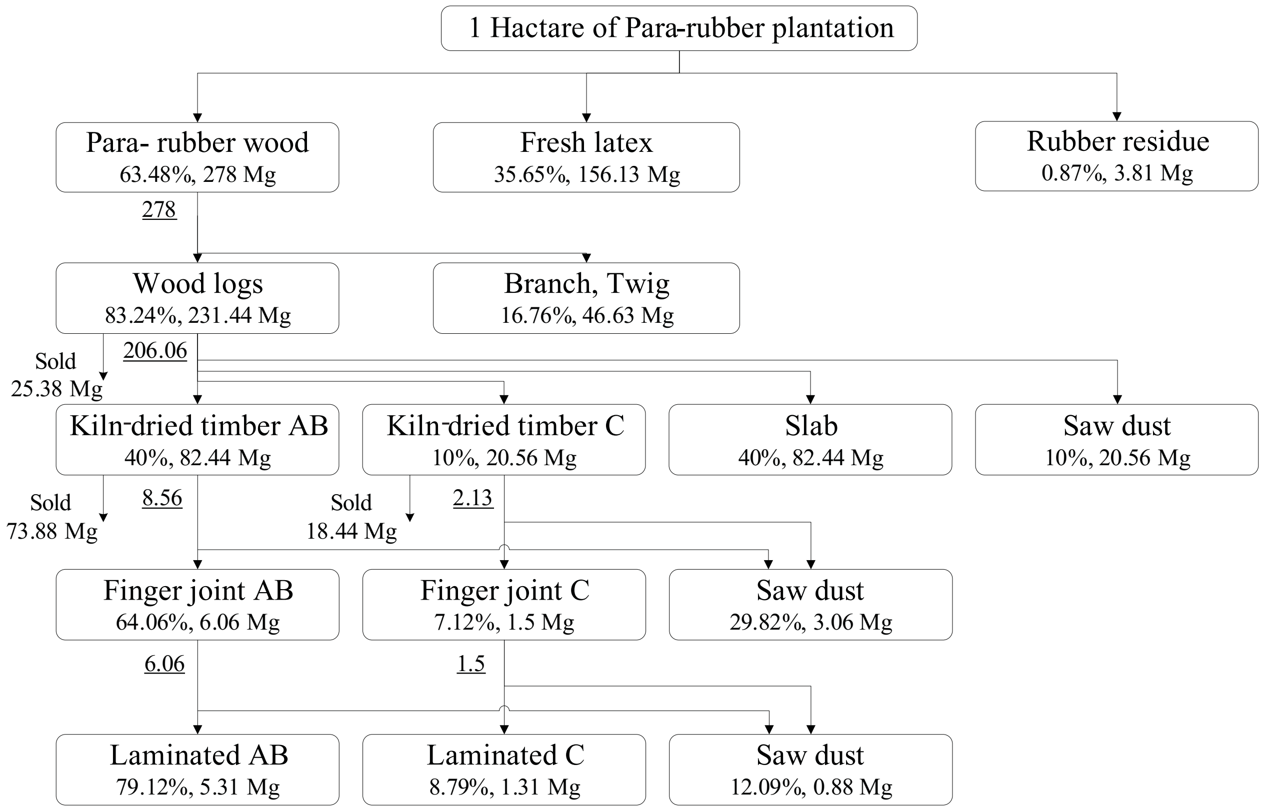


Fig. 2. Utilization of para-rubber wood.

used in rubber plantations. By applying the same mass allocation ratio of this study to the GWP of above-mentioned literature, approximately 1.805 kg rubber wood and rubber residue are generated for every one kg of produced flesh latex, 0.072 kg CO_2-eq per kg is GWP of para-rubber wood, here, about 0.02 kg higher than the present research. Puettmann and Wilson [26] studied LCI of wood production used for building materials, i.e. lumber, kiln-dried timber, and glue-laminated timber, but the LCIA was not integrated in this literature. Using their cradle-to-gate LCI data, i.e. energy requirement, emission to air, emission to water, and emission to land, as input to SimaPro with the same method of the present research, it found that the GWP values of lumber, kiln-dried timber, and glue-laminated timber are 0.3193, 0.7400, and 0.9935 kg CO_2-eq per kg of product, respectively.

Table 7. The five-year average price (2008-12) of para-rubber wood product (USD/kg product).

Products	USD per kilogram
Para-rubber wood	0.06
Fresh latex	3.09
Rubber residue	2.88
Para-rubber wood logs	0.07
Branch, Twig	0.04
Kiln-dried timber AB	0.5
Kiln-dried timber C	0.25
Slab	0.03
Saw dust	0.03
Finger joint AB	0.74
Finger joint C	0.37
Laminated AB	1.33
Laminated C	0.71

Comparative findings indicate that GWP of this study is much less than of that of Puettmann and Wilson's study, about six times for green lumber and kiln-dried timber, and about three times for glue-laminated timber. This difference might be a result of the different study boundary as the present study does transfer some of the impacts by mass allocation to fresh latex, while Puettmann and Wilson's study did not (have no co-product to allocate). In addition, Puettmann concerned only environmental impact from energy use, but this study includes other impacts originating from chemicals, pesticides, herbicides, etc. For saw dust, the only available reference to compare with present research is the wood chip database from JEMAI Pro. After adjusting the electricity impact factor by using Thai national databases, it indicated that GWP per kg of wood chip is 0.0735 kg CO_2-eq, which is much lower than average of the present result, because saw dust of this industry is a co-product of the downstream process.

Although this research did not include the carbon sequestration in GWP result, some literature provided

Table 8. LCIA characterization result of 1 kg product (by mass allocation method).

Process	Product 1 kg	GWP	ADP	AP	EP	ODP
Plantation	Para-rubber wood Flesh latex Rubber residue	0.0504	0.1920	0.3736	0.3833	2.27E-06
Felling	Wood logs Branch, Twig	0.0614	0.2651	0.4942	0.3942	2.27E-06
Mill saw	Kiln-dried timber AB Kiln-dried timber C Slab Saw dust	0.1058	0.4199	0.6523	0.4889	2.93E-06
Finger joint	Finger joint AB Finger joint C Saw dust	0.2610	0.6789	0.8778	0.5233	2.96E-06
Laminate	Laminated AB Laminated C Saw dust	0.3509	1.0679	1.1810	0.4993	3.42E-06

GWP = Global Warming Potential (kg CO_2 eq)
EP = Eutrophication Potential (kg PO_4 eq)
ADP = Abiotic Depletion Potential (kg Sb eq)
AP = Acidification Potential (kg SO_2 eq)
ODP = Ozone Depletion Potential (kg CFC-11 eq)

interesting data that could be useful for further study. In high-intensity sunlight, mature leaf of rubber trees can consume CO_2 at a rate of 10-15 μ mole-m^{-2}-s^{-1}, compared to a range of 5-13 μ mole-m^{-2}-s^{-1} of other photosynthetic plants [27]. By 2050, the areas of lands dedicated to rubber and other diversified farming systems could more than double or triple, largely by replacing lands now occupied by evergreen broadleaf trees. The conversion of both primary and secondary forests to rubber threatens biodiversity and may result in the reduction of total carbon biomass [28-30].

Environmental impacts and revenue per one hectare of this industry in each process and their ratio are shown in Table 9 and Fig. 3. It demonstrates that the plantation process is the largest portion of all considering environmental impacts of this study, mainly from the use of fertilizers and pesticides. Cultivation triggers the most impact on the environmental in all aspects; however, it is the step that causes the most added values as well. More than 90% of this industrial revenue comes from latex. Average total revenue of one hectare for the entire lifetime (25 years) of para-rubber is about $500,000 USD. Almost half of this is spent on operating cost, fertilizers, and labor.

To describe how the processes influence the structure of impact categories, major emission sources of this industry can point to eight activities in each life cycle step:
1) Direct emission
2) Fertilizer production
3) Chemical production
4) Biomass fuel production
5) Fossil fuel production
6) Transport fuel production
7) Electricity
8) Miscellaneous

It should be noticed that, in this case, direct emission brings about environmental impact from combustion products (CO_2, SO_2 generated by stationary or mobile machinery, etc.) and chemical or biological reaction products (N_2O from fertilizer or CH_4 from decay, etc.). Fertilizer production, chemical production, and fuel production activities are classified into three different

Table 9. Impact and revenue of each processes per one hectare.

Process	GWP	ADP	AP	EP	ODP	Value added (USD)
Plantation	22,089.11	84.08	163.62	167.87	9.92E-04	509,110.40
Felling	3,048.59	20.32	33.53	3.04	2.08E-08	1,352.24
Mill saw	9,142.77	31.89	32.57	19.51	1.37E-04	35,824.45
Finger joint	1,656.14	2.76	2.41	0.37	2.51E-07	281.20
Laminate	682.88	3.58	3.11	0.30	6.27E-06	3,056.24
Total	36,619.49	142.64	235.24	191.08	1.14E-03	549,624.53

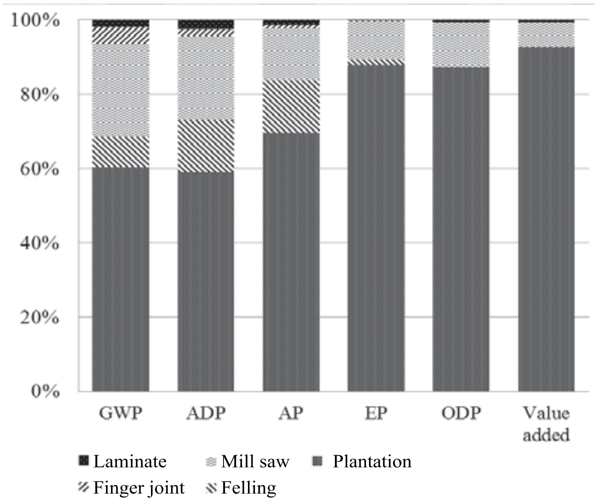


Fig. 3. Contribution of environmental impacts and value added for each process.

groups. Chemical production activity encompasses acquisition of all consumable chemicals except fertilizer and fuel, namely pesticide, herbicide, and lubricating oil, etc. Environmental impact activities from fuel are divided to three groups:

– Biomass fuel is fuel from biogenic matters (renewable such as sawdust and wood slab), excluding fossil products (non-renewable)
– Transport fuel represents any kinds of fuels (renewable or non-renewable) used for transportation purposes
– Electricity is imported electrical energy from external suppliers (provincial electricity authority, industrial estate authority, etc.).

Other consumable parts and materials, such as saw blade, tap water, etc., are categorized as miscellaneous.

Shown in Fig. 4, each chart indicates five environmental impacts, whose distance along the radius direction of geometry signifies the contribution percentage increasing as the logarithmic scale from zero at the center to 100 at most. Symbols on the chart present eight key activities mentioned above. With respect to plantation and fertilizer, production is the activity that contributes to all environmental impacts of this study, especially for ozone layer depletion. Direct emission presents the distinctive effect on AP and EP aspects, which is mainly caused by the use of fertilizers containing nitrogen and potassium.

Chemical manufacturing is one of the significant activities that cause GWP environmental impact. In this case, GWP impact comes from the production of pesticides and herbicides used for preventing, destroying, and mitigating any pests and unwanted plants. Other activities such as fuel production also can be seen as a source of impacts, but rather insignificant. Three anthropogenic sources that are the key causes of environmental impact in felling period are direct emission, fossil fuel production, and transport fuel production. Direct emission which affects GWP, EP, and AP occurs from fuel combustion including transport fuel, fuel used for tractors, and fuel used for chainsaws. This direct emission is proportional to fossil fuel and transport fuel production. ADP impact mostly originates from both transport fuel and fossil fuel production. Environmental impacts resulting from the acquisition of the chemicals can be observed at this stage, but not outstanding at less than one percent. ODP impact is completely small as cannot be observed at this stage.

As can be noticed in Fig. 4, there are many activities contributing to the environmental impact of the sawmill process, but it is mainly due to the use of biomass energy. Biomass consumed in this stage is saw dust and wood slab used as fuel to generate steam for the kiln-dry process. These biomasses actually are co-products from the mill saw and other processes. The activity of the production of biomass affects all categories. Chemical production activities are clearly affected by ODP, and the top contributing chemical is borax used for wood preservation. There are also other chemicals that are sources of indirect emissions, for instance the paint used to identify the type and size of logs and kiln-dried timber products, chemicals used in boilers, and those used for bleaching, etc. For finger joint and lamination, environmental impacts mostly come from electricity and chemicals such as adhesives, hardeners, etc.

Fig. 5 demonstrates the single score impact of each procedure evaluated by summation of all normalized scores of five impacts. Aggregate characterized score of each category is used as its normalization factor, for example, 36,619.49 for GWP, 142.64 for ADP, and so on. By using equal weighting for all impact categories, it is found that the plantation process shows the most single-score impact at 3.6403, and the smallest is the laminating process at 0.0640. The advantage of using single score in environmental impact assessment is not only that it is easy to communicate the impact number and help clarify the relative impact of a substance in a given context, but also gives the maximum value of impact, which is necessary for eco-efficiency analysis. The maximum single impact score of five categories is five, and the average score is essentially one. From Fig. 5, it reveals that – according to the plantation process – every category has an impact on single score approximately at the same level. ODP and EP are the apparent impact at this stage. AP and ADP play an important role in the process of felling, while ODP does not. In the mill saw process, GWP and ADP have more contribution than others. Most of those impacts are delivered from biomass and fossil fuel. Again, the GWP and ADP are also a large part of the effect in finger joint and lamination, but the derivation of these effects is from the use of electricity and chemicals.

Eco-Efficiency analysis shown in Fig. 6 x-axis represents the single score impact, while the y-axis represents the increase in value added at each stage (the unit is USD). Each point in the chart has its eco-efficiency value as indicated next to them, which is the ratio between the value added to a single score impact. Point average in this chart is plotting of the average single score, which is equal to one, with the average value added being 109,924.90. Linear line draw past this point is average eco-efficiency line, which for any points on the line has the same eco-efficiency: 109,924.90. Parallel to the eco-efficiency line indicates different eco-efficiency. Two straight lines drawn vertically and horizontally, which intersect at point average, dividing the chart into four quadrants, the upper left is fully eco-efficiency and the bottom right is fully non eco-efficiency. The average eco-efficiency line divides the bottom left and upper right quadrants into two zones, half eco-efficiency and half non eco-efficiency. The results of the calculations showed that the eco-efficiency of the plantation is the highest, which is more than double the mill saw and lamination. Eco-efficiency of the felling process and finger joint process is quite similar to each other and about 30 times less than that of the plantation. From Fig. 6, it indicates that none of the processes is fully eco or fully non eco. Only the plantation is half eco-efficiency process and others are half non eco-efficiency. From the chart, it also gives us the guideline of further development in the future by using the sustainable direction. The slope of sustainable line is perpendicular to the average eco-efficiency line, -9.10E-6, which means that every \$1,000 USD of value added increase from now on, at least 0.0091 single impact score should be decreased. If sustainable direction is applied to the plantation process, 91.54 kg CO_2 equivalent has to be removed for every \$1,000 USD increase from the present revenue. Mill saw is a step that has the highest potential to upgrade to be fully eco-efficient. By reducing the amount of low price co-product such as wood slap and

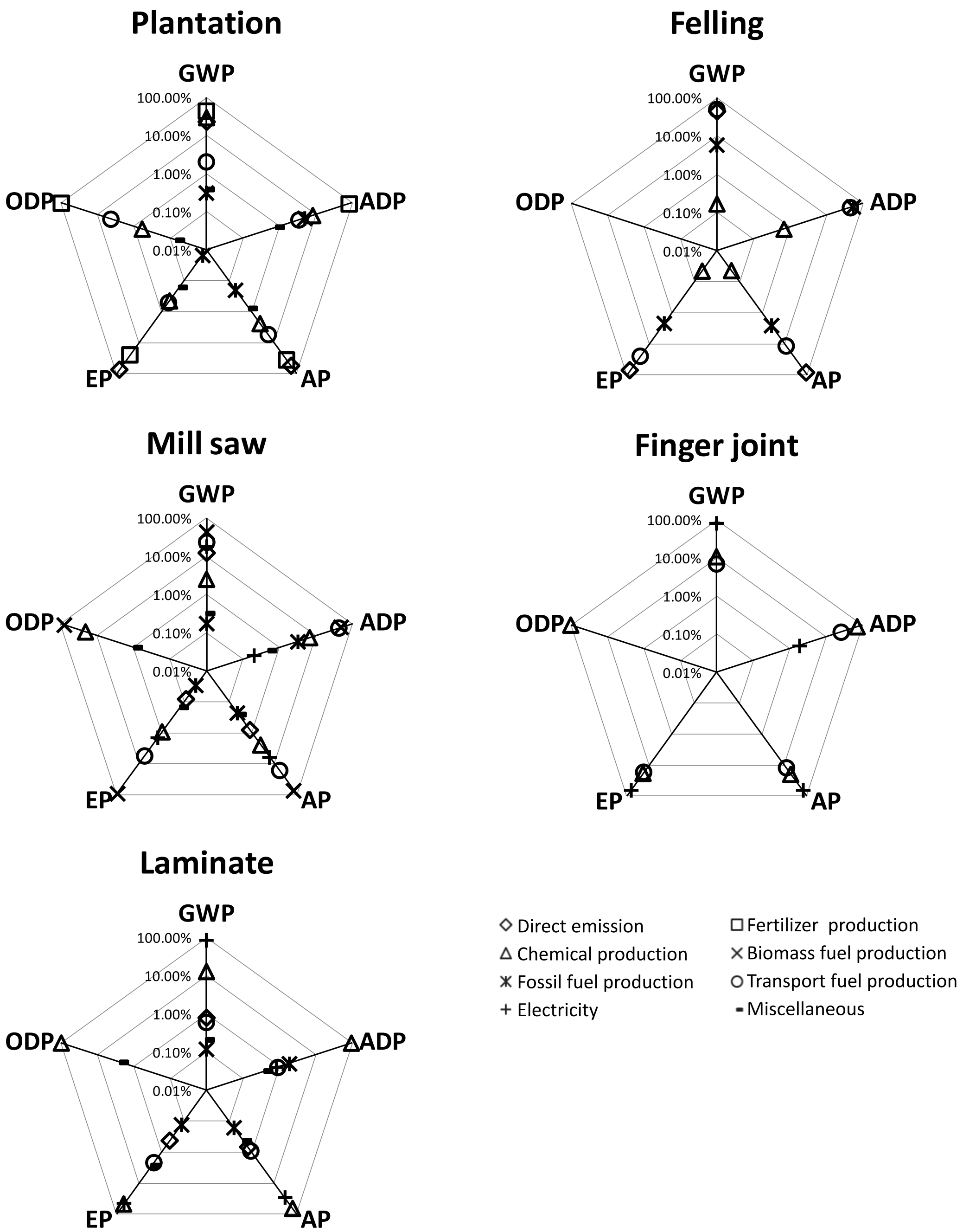
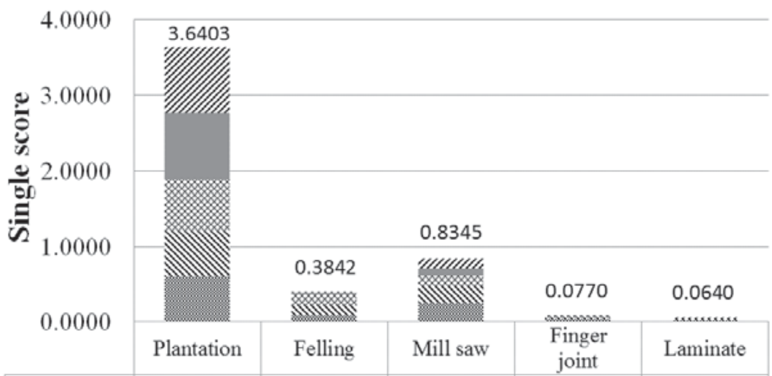


Fig. 4. Sources and proportion of environmental impact.



	Plantation	Felling	Mill saw	Finger joint	Laminate
Norm ODP	0.8735	0.0000	0.1207	0.0002	0.0055
Norm EP	0.8785	0.0159	0.1021	0.0019	0.0016
Norm AP	0.6956	0.1425	0.1385	0.0102	0.0132
Norm ADP	0.5895	0.1425	0.2236	0.0194	0.0251
Norm GWP	0.6032	0.0833	0.2497	0.0452	0.0186

Fig. 5. Single score of individual process base on one-hectare production.

saw dust, and cutting down its energy consumption, value added would be increased along with the reduction of the environmental impact. Although eco-efficiency of the lamination is close to that of the mill saw, the potential of the promotion to the level of full eco-efficiency is proved more difficult because of its lower value added. Therefore, it seems to be that only encouraging this process to be half eco-efficient by reducing environmental impact is more likely possible. The potential to be a higher level of felling and finger joint process, which is half non eco-efficiency, is virtually impossible, because products of both processes are actually low-price intermediate products that necessitate being forwarded to further production. Maintaining low impact on the environment seems to be the best strategy of the two processes mentioned above.

To develop to be higher in eco-efficiency for para-rubber wood industry, several approaches can be implemented. In plantations, yield of lumber is the main factor affecting eco-efficiency. To decrease wood failure of small logs from growth stress, split and twist, and girdling stand tree (hewing a tree around the trunk to make it dry out) should be employed. This technique

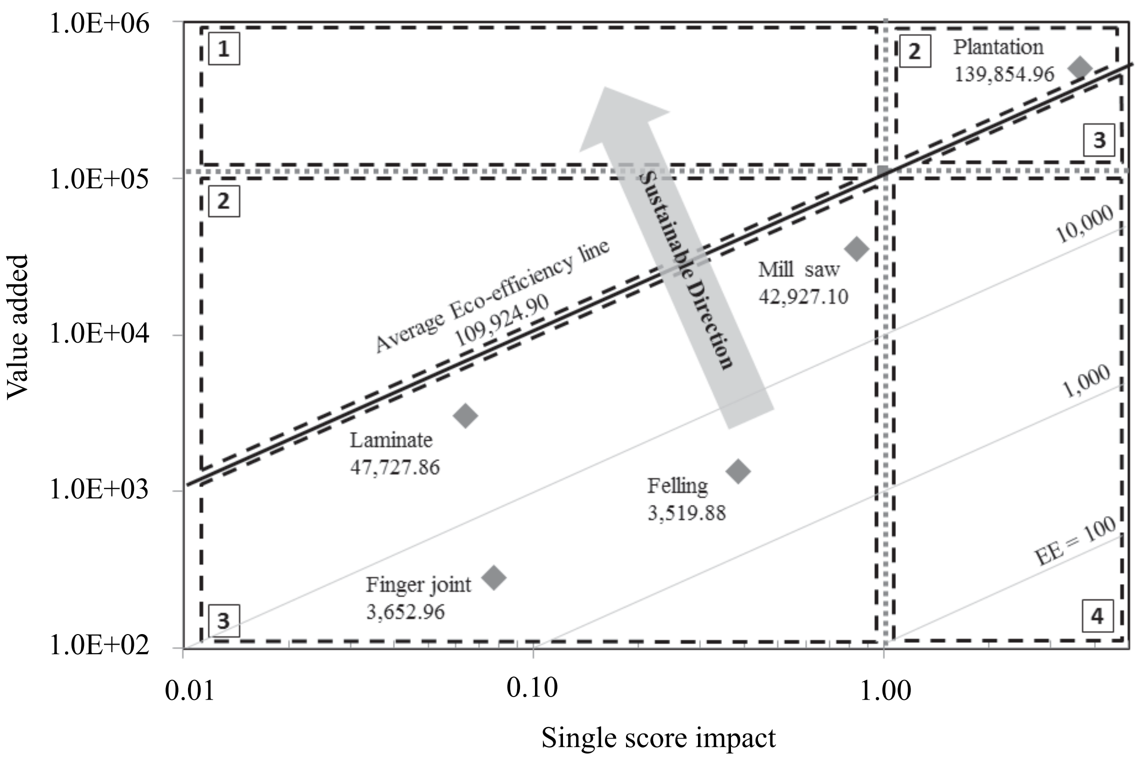


Fig. 6. Eco-efficiency analysis: 1) fully eco, 2) half eco, 3) half non-eco, and 4) fully non-eco.

makes moisture content decrease, therefore decreasing stress of wood, reducing failure in the felling process. In the saw mill process, there are many techniques to prevent twisting or end-splitting. For example, first make sawing log into the large size, then saw again to the required size if needed. Although wood preservation by chemicals is an inevitable process for para-rubber wood products, only to soak it in water, then singe it enough for open-air use. To remove moisture content in timber after chemical treatment, the kiln-dried process is necessary. Some energies may lose by conduction through walls and ceiling, convection with moist air released to the atmosphere, and also radiation. Proper heat ventilation and insulation of the kiln can reduce energy used in this process.

Conclusion

Although para-rubber wood is concerned as an environmentally friendly product, it has proof from research that the production of this industry affects the environment in various aspects. Mass allocation cannot demonstrate the difference of product environmental impacts per kilogram if they are made from the same process. Therefore, assessment of the environmental impact of each process is considered more appropriate. Cultivation seems to have the most impact on the environment due to the use of fertilizers and chemicals. However, in terms of eco-efficiency, a plantation is found to be a reasonable process, when economic considerations are also included, because of high revenue from flesh latex. Mill saw is a step that has the highest potential to develop to be fully eco-efficient, while the others are deemed more difficult. This research does not take storage CO_2 in wood into account, which can be excluded from GWP impact. Additionally, economic allocation should be performed in further research to compare with the results from mass allocation. Finally, social impact is necessary to be included by using social LCA for sustainability evaluation.

Acknowledgements

Financial support of this research was subsidized by a grant from the Ministry of the National Science and Technology Development Agency and the Department of Chemical Engineering, Faculty of Engineering, Thammasat University. The authors would also like to thank the Coordinating Center for Thai Government Science and Technology Scholarship Students for the scholarship arrangement.

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