# Appendix A

Table A1 Specifications of equipment used in the whole tree and forest residue pathways

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Equipment Specification** | **Units** | **Whole Tree** | **Forest Residue** | **References** |
| **Type** |  | Feller | Forwarder | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| **Equipment name** | Model | John Deere 853J | Komatsu WA 250-6 |
| **Lifetime productivity** | dry tonne of biomass | 95812.5 | 101200 |
| **Lifetime fuel consumption** | L diesel | 514650 | 416000 |
| **Lifetime** | hours | 10950 | 16000 |
| **Dedicated equipment required** | N/A | 18 | 17 |
| **Equipment weight** | tonne | 29.427 | 11.82 |
| **Steel in each equipment** | tonne | 28.84 | 11.58 |
| **Type** |  | Chipper | Chipper | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| **Equipment name** | Model | Morbark 50/48 | Nicholson WFP 3A |
| **Lifetime productivity** | dry tonne of biomass | 270000 | 252000 |
| **Lifetime fuel consumption** | L diesel | 900000 | 990000 |
| **Lifetime** | hours | 9000 | 9000 |
| **Dedicated equipment required** | N/A | 6 | 7 |
| **Equipment weight** | tonne | 28.74 | 59 |
| **Steel in each equipment** | tonne | 28.16 | 57.82 |
| **Type** |  | Skidder | N/A | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| **Equipment name** | Model | John Deere 748 H | N/A |
| **Lifetime productivity** | dry tonne of biomass | 90000 | N/A |
| **Lifetime fuel consumption** | L diesel | 540000 | N/A |
| **Lifetime** | hours | 12000 | N/A |
| **Dedicated equipment required** | N/A | 19 | N/A |
| **Equipment weight** | tonne | 14.64 | N/A |
| **Steel in each equipment** | tonne | 14.35 | N/A |

Table A2 Data inventory for raw materials, fuels, plant construction, and road construction

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Impact Factors | Data Inventory | Units | Values | References |
| Steel energy & emissions factors | Energy required to produce 1 tonne of steel | GJ / tonne | 34 | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| CO2eq emissions per tonne of steel | kg CO2eq /tonne | 2495.22 | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| Aluminum energy & emissions factors | Energy required to produce 1 tonne of steel | GJ / tonne | 39.15 | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| CO2eq emissions per tonne of steel | kg CO2eq /tonne | 3467 | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| Concrete energy & emissions factors | Energy required to produce 1 tonne of steel | GJ / tonne | 0.863 | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| CO2eq emissions per tonne of steel | kg CO2eq /tonne | 120 | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| Diesel energy & emissions factors | Lower heating value | MJ/L | 35.98 | (Pellegrini et al. 2013) |
| CO2eq emissions per liter of diesel | kg CO2eq /L | 3.61 | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| Energy required to produce 1 liter of diesel | GJ / L | 0.046 | (Kabir and Kumar 2011; Mahbub et al. 2017) |
| Plant construction material quantity | Steel | tonnes | 2618 | calculated |
| Aluminum | tonnes | 8092 | calculated |
| Concrete | tonnes | 22 | calculated |
| Primary road construction energy & emissions factors | Energy required to construct 1 km road | GJ /km | 1731 | (Kabir and Kumar 2012; Stripple 2001)  |
| CO2eq emissions from construction of 1 km road | kg CO2eq /km | 403845 |
| Secondary road construction equipment | Crawler tractor operating hours | hours/km | 70 | (Winkler 1998)  |
| Dedicated tractor required | N/A | 0.71 | calculated |
| Tractor fuel consumption | L/hour | 23 | (Winkler 1998) |
| Tertiary road construction equipment | Crawler tractor operating hours | hours/km | 100 | (Kabir and Kumar 2012; Winkler 1998) |
| Dedicated tractor required | N/A | 0.68 | calculated |
| Tractor fuel consumption | L/hour | 23 | (Winkler 1998) |

# Appendix B

Wong et al. (2016) considered the average annual precipitation (rainfall) as the water source for the forest biomass growth in the Western province of Alberta, Canada. They assumed the overland flow from the western forests small enough to be neglected and considered the average annual precipitation to be roughly same as the amount of evapotranspiration. Wong et al. calculated the water use factor for the forest biomass growth by using the following equation:

(B1)

Here, water use factor = water required for biomass growth (L H2O/ kg dry wood)

% allocation = 100% allocation for whole tree and 20% allocation for forest residue (since forest residue yield is assumed to be 20% of the whole tree harvest (Kumar et.al 2003; Mahbub et al. 2017)

time to harvest forest biomass = 100 years, the rotation required for whole tree harvest (vs forest residues, which are harvested annually) (Mahbub et al. 2017)

biomass yield = amount of biomass growth per year with the average annual rainfall

# Appendix C

PROMETHEE outranking method

The PROMETHEE outranking method has been used in this study to compare different alternatives or pathways. In this method, first all criteria (indicators) are assigned weights that have been decided by the decision-maker, then a preference index is calculated for all the pathways considering all the criteria and the pathways are ranked. In this study, the best pathway was selected based on the net outranking score. This method relies on the assumption that the higher the score the better the performance of the pathway (the more sustainable the pathway) (Fülöp 2005).

This study develops a base case scenario to compare two different OME pathways based on nine different sustainability criteria (indicators).

*Step 1: Preference Function*

The two pathways are compared in terms of each criterion (indicator) and the differences in estimates on a specific indicator are converted to a degree of preference from 0 to 1, 0 being not preferred at all to 1 (strictly preferred) by using a preference function.

The preference function of the whole tree pathway (WT) over the forest residue pathway (FR) on a particular criterion $i $ is given by Fülöp (2005) as

$0\leq P\_{i}(WT,FR)\leq 1$

where

$P\_{i}(WT,FR)=0$; indicates incomparability between two pathways,

$P\_{i}(WT,FR)≈0$ ; indicates weak preference of WT over FR,

$P\_{i}(WT,FR)≈1$ *;* indicates strong preference of WT over FR,

$P\_{i}(WT,FR)=1$ ; indicates strict preference of WT over FR.

The preference function can thus be defined as the difference between the evaluations of the two pathways on a particular indicator (Fülöp 2005). Thus the preference function of the whole tree pathway (WT) over the forest residue pathway (FR) on a particular criteria *i* is given by Fülöp (2005) as

$P\_{i}\left(WT,FR\right)=p\_{i }(WT\_{i}-FR\_{i})$

where $p\_{i }$ is a non-decreasing function and $p\_{i }(WT\_{i}-FR\_{i})$ $=0 $ when $(WT\_{i}-FR\_{i})\leq 0$and$0 \leq p\_{i }(WT\_{i}-FR\_{i})\leq 1$when $\left(WT\_{i}-FR\_{i}\right)>0$.

Usual and linear preference functions are used in this study. For a usual preference function, incomparability occurs only when the difference between the evaluations of the two pathways on a specific indicator is 0. When the deviation is different from 0 the pathway with the higher value is strictly preferred over the lower valued one (Brans and Vincke 1985).

Usual Preference Function: $p\_{i }\left(WT\_{i}-FR\_{i}\right)=\left\{\begin{array}{c}0,p\_{i }(WT\_{i}-FR\_{i}) \leq 0\\1,p\_{i }(WT\_{i}-FR\_{i}) >0\end{array}\right.$

Linear preference functions require indifference (Q) and preference (P) thresholds to make the preference decision more realistic. In linear preference, indifference occurs until the deviation between evaluations exceed the indifference threshold, and above this the threshold preference increases progressively until the deviation equals the sum of the two thresholds (Brans and Vincke 1985).

Linear Preference Function: $p\_{i }\left(WT\_{i}-FR\_{i}\right)=\left\{(\begin{array}{c}0, p\_{i }\left(WT\_{i}-FR\_{i}\right)\leq Q\\\left(p\_{i }\left(WT\_{i}-FR\_{i}\right)\right)-Q)/P,\\1,p\_{i }\left(WT\_{i}-FR\_{i}\right)\geq Q+P \end{array}\right.Q\leq p\_{i }\left(WT\_{i}-FR\_{i}\right)\leq P$

 *Step 2: Multi-criteria Preference Index*

A multi-criteria preference index compares a pair of alternatives over all criteria. Preference index $π\left(WT, FR\right)$ for WT over FR, taking into account nine criteria (indicators), is defined as

$π\left(WT,FR\right)=\sum\_{i=1}^{m}w\_{i}$ $P\_{i}\left(WT,FR\right)$

where $w\_{i}>0 and w\_{i}$ is normalized weight assigned to criteria iand $m=9. $

The preference index is a value again between 0 and 1 to demonstrate the preference of WT over FR considering all the weighted criteria (indicators).

For example,

$π\left(WT,FR\right)$ =0 indicates the sum of all the $P\_{i}\left(WT,FR\right)$ values equals 0. WT is never preferred over FR for any criteria.

$π\left(WT,FR\right)≈0$ indicates a weak preference of WT over FR.

$π\left(WT,FR\right)≈1$ indicates a strong preference of WT over FR.

$π\left(WT,FR\right)$ =1 indicates the sum of all the $P\_{i}\left(WT,FR\right)$ values equals 1. WT is strictly preferred over FR for all criteria. The boundary conditions to calculate the preference indices are

$π\left(WT,WT\right)=0$

$0\leq π\left(WT,FR\right)\leq 1$

$0\leq π\left(WT,FR\right)+π\left(FR,WT\right)\leq 1$

*Step 3: Partial and Complete Ranking of Alternatives*

Two outranking flows are used to rank the alternative pathways, i.e., positive outranking flow and negative outranking flow. The positive and negative outranking flows for WT over FR are given by equations C1 and C2 (as found in Fülöp 2005).

$∅^{+}(WT)=\frac{1}{n-1}\sum\_{k=1}^{n}π\left(WT,FR\right)$ (C1)

Here *n* stands for the number of pathways. In this study $n=2.$ The positive outranking flow $∅^{+}(WT)$ determines how much the WT pathway outranks the other pathway. The larger the value of $∅^{+}\left(WT\right), $the stronger the pathway. The negative outranking flow is given as

$∅^{-}(WT)=\frac{1}{n-1}\sum\_{k=1}^{n}π\left(WT,FR\right)$ (C2)

The negative outranking flow $∅^{-}(WT)$ determines how much the WT pathway is outranked by the other pathway. The lower the value of $∅^{+}\left(WT\right), $the stronger the pathway.

Both the PROMETHEE I partial ranking and the PROMETHEE II complete ranking were used to rank the alternatives. According to the PROMETHEE I partial ranking, WT is preferred over the FR pathway if$ ∅^{+}\left(WT\right)\geq ∅^{+}\left(FR\right) $, $∅^{-}(WT)\leq ∅^{-}(FR)$ and one of them is a strict inequality. The WT and FR pathways are indifferent if $∅^{+}\left(WT\right)=∅^{+}\left(FR\right)$ and$ ∅^{-}\left(WT\right)= ∅^{-}(FR)$*.* Otherwise, the WT and FR pathways are incomparable (Fülöp 2005).

According to the PROMETHEE II complete ranking, the net outranking flows for the whole tree pathway $∅\left(WT\right)$ and the forest residue pathway $∅\left(FR\right)$ given by equations C3 and C4 determine the preference of one pathway over the other (Fülöp 2005).

$∅\left(WT\right)=∅^{+}\left(WT\right)-∅^{-}\left(WT\right)$ (C3)

$∅\left(FR\right)=∅^{+}\left(FR\right)-∅^{-}\left(FR\right)$ (C4)

If $∅\left(WT\right)>∅\left(FR\right),$ WT is preferred over FR. The pathways are indifferent if$ ∅\left(WT\right)=∅\left(FR\right)$. The pathway with the largest net outranking flow value $(∅)$ is considered to be the best sustainable pathway over the others.

**Appendix D**

Table D1 Social impacts assessments for whole tree and forest residue pathway

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Unit operations | Pathways | Volume of wood chips involved in the unit operation for 20 years  | Total time involved in a unit operation in 20 years  | Employment potential± | Biomass involved  | Labor cost€ |
| m3 | hours | hours/m3 | dry tonne/hour | $/dry tonne |
| Biomass Growth | WT | 20320944 | 876000 | 0.043 | 3.2 | 8.17 |
| FR | 16990738.8 | 876000 | 0.05 | 3.2 | 8.17 |
| Biomass Harvest  | WT | 20320944 | 786666.6667 | 0.038 | 3.56 | 7.33 |
| FR | 16990738.8 | 542687.2043 | 0.03 | 5.16 | 5.06 |
| Biomass Transportation  | WT | 20320944 | 672656.0203 | 0.03 | 4.16 | 6.27 |
| FR | 16990738.8 | 2294751.977 | 0.14 | 1.22 | 21.4 |
| Chemical Conversion | WT | 20320944 | 180979.6697 | 0.01 | N/A | 34.91 |
| FR | 16990738.8 | 223258.9455 | 0.01 | N/A | 34.91 |
| OME Transportation | WT | 20320944 | 632206.16 | 0.03 | 4.43 | 5.89 |
| FR | 16990738.8 | 632206.16 | 0.04 | 4.43 | 5.89 |

±The employment potential for a particular unit operation was assessed by dividing a ratio of operation time by the biomass volume (m3) involved in the operation.

€For the harvesting and transportation operations, employee wages were calculated based on hours of operation and hourly labor rates. The wages and benefits for the harvesting and transportation operations are estimated to be $26.11/hour ([Canada-Visa 2014](#_ENREF_11)), equivalent to the required skill level of the job.