**Petitmermet Log Length System (LLS) model implementation in OpCostIT – Operations Cost Model – interim tethered edition**

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This first part of this document summarizes the Petitmermet equations and how they are adapted for use in an interim OpCost model. The second part, beginning on [page 7](#Implementation_Plan), outlines a plan for implementing this system in the new OpCost framework. We recognize that this system is not necessarily generally applicable in all situations and it is not intended to permanently replace all the other models included in OpCost. It addresses a short term and urgent requirement to generate plausible cost numbers for an overdue analysis.

The “Petitmermet tethered system” model applies on both gentle and steep slopes, though the coefficients are different because on steep slopes, the cut-to-length harvester requires additional tethering time for moving between corridors and the forwarder operates more slowly when tethered. The system consists of a tether (anchored machine with cable to connect to the logging equipment—harvester and forwarder). The forwarder is also used to load trucks at the landing. The equations for harvester cost, forwarding cost and loading cost were developed for a study where it was important to separate merchantable logs from biochar feedstock logs, because the latter are more time consuming to handle per unit volume and even more so per unit value, so the inputs to the cost equations for forwarding and loading handle these volume components separately. Because BioSum accounts for trees, not logs, some additional modeling was needed to develop forwarding and loading costs because we do not know how much volume is merchantable vs biochar feedstock so cannot directly use Joshua’s forwarding and loading equations.

Because BioSum currently needs to specify gentle and steep slope systems separately, there are two entries for tethered systems in the harvest\_methods table in REF\_MASTER:

| **harvest\_methods** | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **HarvestMethodID** | **STEEP\_YN** | **Method** | **Description** | **biosum\_category** | **min\_yard\_distance\_ft** | **min\_tpa** | **min\_avg\_tree\_vol\_cf** |
| 9 | N | Tethered Harvester | Tethered | 3 | 150 | 20 | 8 |
| 54 | Y | Tethered Harvester | Tethered | 3 | 150 | 20 | 8 |

Equations will be provided separately for these two variations of the same system, where appropriate, (one accounting for tethering costs, the other not).

**Harvester Equations**

These are very straightforward to use. From Petitmermet 2018, page 58:

Harvester time is calculated as:

(2) ht = 1.43tw + 0.25hdi

Where: ht is the harvester time required in productive machine minutes

tw is the total weight of material handled in green tonnes, and

hdi is the distance traveled in meters.

**The travel distance, hdi, is held constant at 531 meters per acre and was calculated as two times the linear distance required to cover one acre with a corridor 15 meters wide. This may overestimate the actual distance required on flat ground where opportunistic wandering could allow the harvester to move from section to section without backtracking. It may also underestimate the actual distance on short, steep corridors where it fails to account for travel time between corridors. The harvester time in minutes is then converted to hours and multiplied by either $278.95 per productive machine hour for tethered operations or $212.47 per productive machine hour for untethered operations, producing a harvester cost per hectare.**

**So to calculate the cost per acre of the harvester (from Excel sheet):**

1. **Calculate Total weight (TW) as CONVERT((“Small log trees per acre”\*”** **Small log trees average volume(ft3)”\*”** **Small log trees average density(lbs/ft3)”),"lbm","ton")  
     
   where CONVERT changes pounds to metric tons (tonnes, but labeled as ton in the Excel conversion function)**
2. **Calculate Merchantable Weight (MW) as TW \* Small log trees MerchAsPctOfTotal**
3. **Calculate Harvester Time (HT\_minutes) as =(1.43\* MW + 0.25\*531)  
   The product of two scalars is left as written to remind us of the embedded assumption about travel distance per acre (531 meter), which a user may want to modify at some point. Note that there is no use of yarding distance in harvester cost calculations.**
4. **Calculate Harvester Hours (HT\_hours) as HT\_minutes/60**
5. **Calculate Harvester Cost in $/acre either for Untethered (harvest method #9) systems as HC\_U = $212.47 \* HT\_hours or for Tethered (harvest method #54) systems as HC\_T = $278.95 \* HT\_hours**

**Forwarder time model**

I relied on 227 non-zero SLT volume, low slope (<35%) cases from Rx 304 (thin from below at cycle 4) FIA dataset built by Joshua Petitmermet for the Upper Klamath region in Oregon. Model needed because Joshua’s tethered system model assumes that volume can be distinguished between sawlogs (wood in logs of merchantable species at least 8 feet long with a small end diameter of 4”) and biochar feedstock (wood 8 feet and longer with any diameter that does not qualify as sawlogs. In BioSum, we have only tree characteristics, not log characteristics, and in OpCost input, a fairly limited summary of tree characteristics.

The forwarder time model has both a distance component and a weight component (from Petitmermet 2018):

(3) ft = 0.05fdi + 2.19sac + 4.06pac on tethered ground, and

(4) ft = 0.01fdi + 2.19sac + 4.06pac on untethered ground

Where ft is the forwarding time required in productive machine minutes

sac is the weight of sawlog material in green tonnes

pac is the weight of feedstock material in green tonnes, and

fdi is the distance traveled by the forwarder in meters.

For this modeling, I took Joshua’s calculated forwarder cost for each stand, divided by $172.22 per productive machine hour for untethered operations to get hours per acre of forwarder time, then multiplied by 60 to get time in minutes and subtracted off the calculated distance component of cost (0.01 times yarding distance in feet) to get Joshua estimated forwarding time due to weight (JEFT\_wt). Note: It is not entirely certain whether or not yarding distance in Joshua’s BioSum project was in feet or meters—I assumed it was in feet. I then fit and evaluated models to estimate JEFT\_wt from merchantable weight per tree calculated as SLT\_Avg\_Vol\_per\_tree\_ft3 \* SLT Avg Density (which is in lbs/ft3) \* Small log trees MerchAsPctOfTotal / 100 and SLT\_Avg\_Vol\_per\_tree\_ft3, as shown below, as a multiplicative (log) model in which predicted and predictor variables are log transformed.

\*\*\* Linear Model \*\*\*

Call: lm(formula = log(Ftime.wt) ~ log(SL.tpa) + log(SL.Merch.gt.per.tree), data =

forwarderTest, na.action = na.exclude)

Residuals:

Min 1Q Median 3Q Max

-0.6535 -0.1412 -0.02998 0.1081 1.011

Coefficients:

Value Std. Error t value Pr(>|t|)

(Intercept) 1.0613 0.1567 6.7728 0.0000

log(SL.tpa) 0.8841 0.0326 27.1297 0.0000

log(SL.Merch.gt.per.tree) 0.6714 0.0233 28.8407 0.0000

Residual standard error: 0.2598 on 219 degrees of freedom

Multiple R-Squared: 0.8629 Adjusted R-squared: 0.8617

F-statistic: 689.4 on 2 and 219 degrees of freedom, the p-value is 0

Forwarder time is converted to forwarder cost per acre by application of the appropriate cost ($172.22 per productive machine hour for untethered operations and $198.11 for tethered operations). While this does not account for differences among plots in the occurrence of noncommercial species (which could affect biochar feedstock proportion, though probably not the size distribution, which is more germane to forwarder handling challenges), and could conceivably be improved, it seems to capture most of the signal and looks a lot better in terms of correspondence with Joshua’s estimates than any arbitrary fixed (independent of avg vol per tree) assumption of merch to feedstock ratios that I explored. The resulting model tracks Joshua’s estimates acceptably:

To calculate forwarder cost:

1. Calculate average merchantable green tons per tree (**AMGTPT**) as:  
   [“Chip tree per acre” \* “Chip trees average volume(ft3)” \* “CHIPS Average Density (lbs/ft3)” \* “CHIPS Average Density (lbs/ft3)” \* (“Chip trees MerchAsPctOfTotal” / 100) + “**Small log trees per acre**” \* “**Small log trees average volume(ft3)**” \* “**Small log trees average density(lbs/ft3**)” \* (“**Small log trees MerchAsPctOfTotal**” / 100) + [“**Large log trees per acre**” \* “**Large log trees average volume(ft3)**” \* “**Large log trees average density(lbs/ft3)**” \* (“**Large log trees MerchAsPctOfTotal**” / 100)] / [2000 \* (“**Small log trees per acre**” + “**Large log trees per acre**” + “**Chip log trees per acre**”)]
2. Apply the above described model for the weight component of forwarder time **FT\_wt**: EXP(1.0613+0.8841\*LN(“**Small log trees per acre**” + “**Large log trees per acre**” + “**Chip tree per acre**”)+0.6714\*LN(**AMGTPT**))
3. Calculate the distance component of forwarder time, FT\_dist. This depends on whether operation is tethered or not.
   1. For untethered, harvest method #9: FT\_dist = 0.01 \* “**One-way Yarding Distance**”/ 3.28
   2. For tethered, harvest method #54: FT\_dist = 0.05 \* “**One-way Yarding Distance**”/ 3.28
4. Combine the two parts of the forwarder equation to get forwarder time **FT** as **FT\_dist** + **FT\_wt**.
5. Convert **FT** to Forwarder Cost (**FC**) which varies by tether status:
   1. For untethered, harvest method #9: **FC\_U** = **FT** \* 177.22
   2. For tethered, harvest method #54: **FC\_T** = **FT** \* 198.11

**Loading Cost**

As mentioned earlier, loading is accomplished with the forwarder in this system. And similar to forwarding costs, Petitmermet provides an equation that differentiates between merchantable and biochar feedstock, so it was necessary to apply assumptions informed by the Klamath biochar BioSum dataset. Petitmermet’s equations are documented as:

Truck loading time is calculated as:

(5) lt = (sac / lsp) + (pac / lpp)

Where: lt is the time spent loading in productive machine hours

lsp is the loading rate for saw material in green tonnes per hour, and

lpp is the loading rate for feedstock material in green tonnes per hour.

A per acre loading cost is then calculated as the loading time multiplied by $213.22 ($172.22 per productive machine hour for the forwarder plus $41 per productive forwarder hour for the idle truck).

We assumed that that sac (merch) is 90% of the weight handled. The calculation approach is then:

1. Calculate **sac** as **AMGTPT** \* 0.90 and **pac** as **AMGTPT** \* 0.10.
2. Utilize Joshua’s recommendations for lsp and lpp to calculate loading time **lt** as (**sac**/59.42 + **pac**/35.29)
3. Calculate loading cost **LC** as **lt** \* 213.22

The numbers track Joshua’s estimates pretty well with the 0.90/0.10 assumption:

Total Cost for this system (before considering chipping) is then:

Untethered Petitmermet: Petitmermet\_U = HC\_U + FC\_U + LC

Tethered Petitmermet: Petitmermet\_T = HC\_T + FC\_T + LC

Comparing total cost developed this way with the costs estimated by Joshua shows acceptable correspondence at all but the highest cost stands:

**Plan for Interim Implementation of Petitmermet 2018 Tethered System in OpCost**

As outlined above, the Petitmermet (2018) equations described above cover three functions:

1. Harvesting (of chip and small log trees),
2. Forwarding of logs from all tree sizes (chip, small and large log), and
3. Loading logs onto trucks. Although this function is also accomplished by the forwarder, for transparency and because when used in this way the forwarder also incurs the time cost of an idle truck that is being loaded, we will calculate this loading cost component separately.

The forwarding equation has different parameters for steep and gentle slopes. As a rule of thumb (subject to later revision and customization), we will call >=40% slope steep, and less than 40% gentle (or low) slope.

Both the harvesting and forwarding equations have higher cost per productive machine hour (PMH) when the slope is steep and equipment is tethered, to account for the time required to move equipment between harvest corridors and the associated de-tethering and re-tethering that must take place. It takes more scheduled machine hours (SMH) for each PMH; hence the higher price per PMH. Time requirements are specified in the equations as PMH.

Two additional machines are needed for this system. Chainsaw felling is needed for large log trees, which are felled, limbed and bucked by a sawyer because they are too large to be handled by the harvester. Chipping is needed to account for the cost of chipping the boles of so-called chip trees (defined thusly in BioSum by a diameter threshold) AND the merchantable parts of small and large log trees that are of a non-commercial species. No limbs are recovered under this system for any tree size on any slope.

The equations to use to represent these two machines for this interim version of OpCost10 are:

1. For Chainsaw costs: Ghaffariyan (Eq.ID=33)
2. For Chipping costs: Bolding (Eq.ID=14)

Finally, there is a need to account for brush cut costs (cutting and scattering trees less than chip size that appear on the FVS cutlist). For this interim version, we will assume 6 seconds of processor time (0.1 minutes) per tree of brush cutting required.

A good reference for understanding what parts of what trees get recovered and utilized (as merch or chips) on what slopes is the TreeProcessorCases page of the processor\_permutations workbook on github under OPCost. Note that the first page of this workbook contains the latest harvest\_methods table as edited by Lesley into BioSum version 5.8.4, and that the harvest method categories appear on page 2.

The rest of this document will detail the steps for calculating time and costs for each machine. Because of differences in what gets handled by each machine in the way of tree sizes, times will be calculated separately for each tree size class and the times summed before computing machine costs. At least for the equations used by this system, this should work as there do not appear to be any scale economies embedded in these equations. Whether or not that holds true for other systems remains to be determined. It will be up to the programmer to decide exactly the most transparent and efficient way of calculating and storing these size class aggregates (for volume, weight, tpa, etc.).

**Harvester Cost**

This applies only to chip and small log trees. The equation that calculates harvester time:

ht = 1.43tw + 0.25hdi

requires tw (total merchantable weight) and travel distance, hdi, which is held constant at 531 meters per acre. To calculate tw (what we will call MerchWtLbs), we need:

1. MerchWtLbs\_SL = Small log trees per acre”\*” Small log trees average volume(ft3)”\*” Small log trees average density(lbs/ft3)” \* “Small log trees MerchAsPctOfTotal”.   
      
   MerchWtLbs\_CT = Chip trees per acre”\*” Chip trees average volume(ft3)”\*” Chip trees average density(lbs/ft3)” \* “Chip trees MerchAsPctOfTotal”.  
     
   MerchWtLbs\_Harvester = MerchWtLbs\_SL + MerchWtLbs\_CT
2. Convert MerchWtLbs\_Harvester to metric tonne weight, as MerchWtTonnes\_Harvester = 0.000453592 \* MerchWtLbs\_Harvester.
3. Apply the equation to get Harvester time in minutes,   
   HT\_minutes = 1.43\* MerchWtTonnes\_Harvester + 0.25 \* 531   
     
   The product of two scalars is retained, as written, to remind us of the embedded assumption about travel distance per acre (531 meter), which a user may want to modify at some point. Note that there is no use of yarding distance in harvester cost calculations
4. Add harvester time to account for brush cut time of 6 seconds per tree, per Joshua Petitmermet  
     
   HT\_minutes = HT\_minutes + (BrushCutTpa \* 0.1)  
     
   Note: BrushCutTpa is an OpCost\_input field  
   Note: This formulation matches what was already in the OpCost code for average tree volume < 4 cu. ft { ifelse(is.na(m$BrushCutTPA), 0, ifelse(m$BrushCutTPA>0, ifelse(m$BrushCutAvgVol<4, m$BrushCutTPA/(10\*60), m$BrushCutTPA/(5\*60)), 0))} for mechanized systems, which is to say, nearly all cases.
5. Calculate Harvester Cost in $/acre, after converting to time to hours, either for Untethered (harvest method #9) systems as   
     
    HC\_DPA = $212.47 \* HT\_minutes/60   
     
   or for Tethered (harvest method #54) systems as   
     
    HC\_DPA = $278.95 \* HT\_minutes/60

**Forwarder Cost**

This section lays out calculation of cost for the use of the forwarder to forward logs of all three size classes. Forwarder time is predicted by both weight of material to be handled and distance, so has two components. The coefficient on distance is different depending on whether system is in untethered (gentle slope) or tethered (steep slope) mode.

1. MerchWtLbs\_LL = Large log trees per acre”\* ” Large log trees average volume(ft3)”\*”Large log trees average density(lbs/ft3)” \* “Large log trees MerchAsPctOfTotal”.   
     
   MerchWtLbs\_SL = Small log trees per acre”\*” Small log trees average volume(ft3)”\*” Small log trees average density(lbs/ft3)” \* “Small log trees MerchAsPctOfTotal”.  
      
   MerchWtLbs\_CT = Chip trees per acre”\*” Chip trees average volume(ft3)”\*” Chip trees average density(lbs/ft3)” \* “Chip trees MerchAsPctOfTotal”.  
     
   MerchWtLbs\_Forwarder = MerchWtLbs\_SL + MerchWtLbs\_SL + MerchWtLbs\_CT  
     
   Note that the CT and SL merch weight was already calculated for use in the harvester cost calculation.
2. Convert MerchWtLbs\_Forwarder to metric tonne green weight, as   
     
   MerchWtTonnes\_Forwarder = 0.000453592 \* MerchWtLbs\_Forwarder.
3. Calculate Trees per Acre for CT, SL and LL trees as  
     
   TPA\_CT = “Chip tree per acre”   
   TPA\_SL = “Small log trees per acre”   
   TPA\_LL = “Large log trees per acre”
4. Calculate Forwarder Time due to weight   
     
   FT\_wt\_CT = IF(TPA\_CT > 0, EXP(1.0613+0.8841\*LN(TPA\_CT)+0.6714\*LN(MerchWtLbs\_CT \* 0.000453592/TPA\_CT)),0)  
   FT\_wt\_SL = IF(TPA\_SL > 0, EXP(1.0613+0.8841\*LN(TPA\_SL)+0.6714\*LN(MerchWtLbs\_SL \* 0.000453592/TPA\_SL)),0)   
   FT\_wt\_LL = IF(TPA\_LL > 0, EXP(1.0613+0.8841\*LN(TPA\_LL)+0.6714\*LN(MerchWtLbs\_LL \* 0.000453592/TPA\_LL)),0)  
   FT\_wt = FT\_wt\_CT + FT\_wt\_SL + FT\_wt\_LL
5. Calculate Forwarder Time due to distance,   
     
   FT\_dist = (0.01 \* “One-way Yarding Distance”/ 3.28) \* IF((“Percent Slope” > Steep By BioSum Threshold), 5, 1))  
   1. Note: The IF THEN ELSE clause chooses 5 if the stand is steep, and 1 otherwise
6. Calculate Forwarder Time  
     
   FT = FT\_wt + FT\_dist
7. Calculate forwarder cost in dollars per acre, after converting to hours, as   
     
   FC\_DPA = (FT/60) \* IF((“Percent Slope” > Steep By BioSum Threshold),198.11,177.22))

**Loading Cost**

This section lays out calculation of cost for the use of the forwarder to forward logs from small and large log trees. Chip trees are not accounted for here because their chipping and loading (blown onto chip vans) cost is accounted for by the chipping cost equation.

1. Calculate MerchWtLbs\_Loader as MerchWtLbs\_LL + MerchWtLbs\_SL
2. Convert MerchWtLbs\_Loader to metric tonne green weight, as   
     
   MerchWtTonnes\_Loader = 0.000453592 \* MerchWtLbs\_Loader
3. Calculate Loader Time in hours (incurred for this forwarder) due to loading,   
     
   **FT\_load = (**MerchWtTonnes\_Loader \*0.9/59.42 + MerchWtTonnes\_Loader \*0.1/35.29)
4. Calculate loading cost in dollars per acre, after converting to hours, as  
     
   LC\_DPA = (FT\_load/60) \* 213.22  
   1. Note that this $213.22/hr reflects $172.22 per productive machine hour for the forwarder (untethered operations at the landing) plus $41 per productive forwarder hour for the idle truck).

**Chainsaw Cost**

We use the Ghaffariyan equation to account for costs of felling large trees. This equation uses calculated average dbh as the basis of computing a per tree felling time. It is important that this average be calculated using only the large log trees in this system. Dbh is currently calculated off of twitch volume, which is for ALL tree size classes, but this would clearly be incorrect in this system, as we are only interested in the mean volume of large trees, so we must calculate a dbh from Large.log.trees.average.vol.ft3, NOT from twitch\_volume.

1. Calculate mean diameter of large log trees, in centimeters, as  
     
   DBH\_LT\_cm = sqrt((” Large log trees average volume(ft3)” + 8.4166) / 0.2679)\*2.54  
   1. Note: this follows the equation found in the OpCost code as applied to twitch volume, that remains to be verified.
   2. Note: the equation is only reliable if dbh in cm is >25; this will likely always be the case for large log trees, but if exception occurs, we need to either set dbh to 25 or warn the user that chip cost was omitted for this case.
2. FellLimbBuckTime\_minutes\_per\_tree = -1.582+(0.099\* DBH\_LT\_cm))
3. FellLimbBuckTime\_hours = FellLimbBuckTime\_minutes\_per\_tree \* “Large log trees per acre” / 60
4. FLB\_Cost = whatever cost per hour is in the cost table times FellLimbBuckTime\_hours

**Chipping Cost**

We choose to use the Bolding equation for this system, pending the working out of other issues with chipping costs generally in OpCost. This equation requires as input only the total volume to be chipped. Because tops and limbs remain in the forest with this system and boles of merchantable trees are utilized as logs, the volume to be chipped consists entirely of chip tree boles and boles of non-commercial species.

1. ChipVolFt3 = “Chip tree per acre” \* “Chip trees MerchAsPctOfTotal” \* “Chip Trees Average Volume (ft3)” + “Small log tree per acre” \* “Small log trees ChipPct\_Cat1\_3” \* “Small log Trees Average Volume (ft3)” + “Large log tree per acre” \* “Large log trees ChipPct\_Cat1\_3” \* “Large log Trees Average Volume (ft3)”
2. Chipping\_Time\_Hrs\_per\_acre = 0.001 \* ( ChipVolFt3 \* 25)
3. Chipping\_Cost\_DPA = whatever cost per hour is in the cost table times Chipping\_Time\_Hrs\_per\_acre

**Combining the costs**

All of these costs are added up to get per acre harvest costs. In addition, the chipping cost is written to the chipping cost column in the OpCost\_output table (and if appropriate, the OpCost\_Ideal table).