Decreasing specific energy of thermomechanical pulps from reduction of raw materials variability

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ABSTRACT: Wood chip characteristics including species, basic and bulk densities, moisture content, freshness, bark content, and size distribution strongly influence the specific energy consumption (SEC) of thermomechanical pulping. Changes in these characteristics lead to variations in the mass flow rate of the chips fed into the refiner, causing SEC variations. In a typical mill with normal operating conditions, up to 30% of the disturbances in the pulping process can be explained by chip variations. For this paper, researchers used an online measurement system, CMS^E (chip management system, extended version), to monitor chip characteristics to study the effect of chip variability on SEC. Models and simulations were built from pilot experiments and results were validated by mill trials.

Application: This investigation reveals that proper control of chip properties variability, particularly bulk density, can lead to SEC savings of up to 5%.

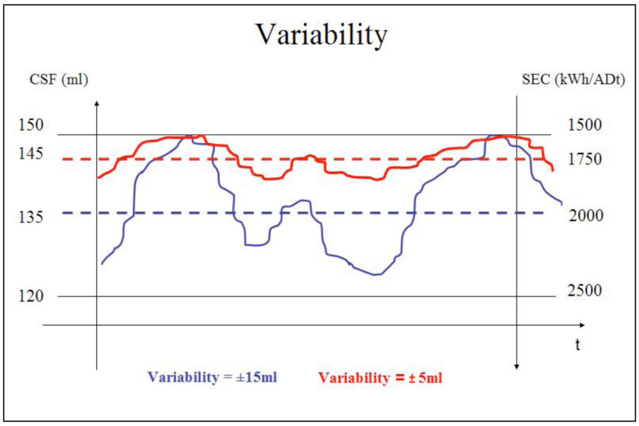
Thermomechanical pulp (TMP) refiners are typically powered by 10-30 MW electric motors. In this process, wood chips are the raw material and variations in their characteristics affect both specific energy consumption (SEC) and pulp quality [1]. The TMP process is used in 80% of newsprint production worldwide. Mechanical pulps must be produced in an energy-efficient manner, not just for cost reduction alone, but also for resource protection purposes. **Table I** shows an estimate of the typical energy consumption for a TMP process using black spruce chips for newsprint production [2].

To satisfy customer demands, pulp produced by a mill usually must be within a range of desired pulp quality characteristics and measurements, such as Canadian Standard Freeness (CSF). This range is typically defined by upper or lower bounds. Because CSF and SEC are inversely related, when the CSF value is near the lower bound, more energy is expended to reach the desired quality. When CSF is near the upper bound, an optimal consumption of energy for an acceptable quality pulp is used. **Figure 1** shows comparative CSF set points and SEC for two hypothetical TMP processes, each with different CSF variability. The process with higher variability (±15 mL) must use a lower CSF set point of 135 mL to remain within the upper CSF limit of 150 mL. However, in the second process, with reduced variability (±5 mL), the CSF set point can be raised to about 145 mL. This results in a potential decrease in SEC (from 2000 to 1750 kWh/air dried ton in this example).

Chip property variability influences CSF variability. Controlling chip variability should help reduce CSF variability, which in turn could lead to reductions in specific energy consumption (Fig. 1). Researches in TMP production usually study the relationships between the process parameters and pulp quality [3–6] and between process parameters and chip

	Steam produced (GJ/air-dried ton)	Electricity consumed (kWh/ air-dried ton)
Chip handling		40
Refiners		2160
Pumps, screens, agitators, blowers		240
Heat recovery	5.5	10
Total consumption	5.5	2450

I. Electricity consumption and steam production in a typical thermomechanical pulp (TMP) process (adapted from [2]).



1. Comparative CSF set points and specific energy consumption (SEC) for some thermomechanical pulp (TMP) processes with different CSF variability.

Wood species	% of total mixture
Black spruce	70%- 90%
Fir	0% - 15%
Pine	0% - 20%
Hardwood	0% - 10%

II. Typical chip mixtures in mills.

characteristics [7–9]. Much less research has been conducted on the relationships between chip characteristics and pulp quality [10], the focus of this paper. For this research, we used a chip management system, extended version (CMS^E) [11] to study the effects of chip characteristics on pulp properties.

EXPERIMENTAL

This study investigated experimental chip mixtures, each consisting of different species proportions and bulk densities. Typical percentages of wood species are in the ranges proposed in **Table II**. The strategy was to create a suitable experimental domain using values that cover the normal range of each species (**Table III**). Five different mixtures were selected. The typical mixture (Mixture 1: 80% spruce, 5% fir, 10% pine, and 5% hardwood) is the most representative at the partner mill and it reflects the normal operating conditions. Mixtures 2 (90% spruce and 10% fir) and 3 (70% spruce, 20% pine, and 10% hardwood) verify the influence of maximum and minimum levels of spruce. Mixtures 4 (75% spruce, 15% fir, 5% pine, 5% hardwood) and 5 (85% spruce, 5% each fir, pine, and hardwood) verify the influence of different levels of fir. **Table IV** shows the dry basic density values of each species used in the calculations for the bulk density of each mixture shown in **Table V**.

We conducted pilot trials at Centre Intégré en Pâtes et Papiers (CIPP; Trois-Rivières, Québec, Canada) such that the process conditions of the partner mill could be recreated as closely as possible. Before entering the refiner, the selected proportions of different chip species (Table III) were measured by the CMS^E to get readings of some of their properties. Each chip sample was washed and then refined in two stages, one pressurized (at 128°C) and one at atmospheric pressure. The plate gap was fixed during the first stage but changed in the second stage to obtain five different SEC and CSF levels. Each trial was repeated to estimate experimental errors. In total, 50 trials were performed, five for each of the five mixtures with repetitions. The pilot refiner used was a Metso CD300 equipped with 12-in diameter plates and a 200 hp electric motor providing a maximum rotational speed of 3565 rpm. Pulp and paper properties were measured at the pilot plant according to PAPTAC standard methods.

RESULTS

Table VI shows the results for all trials, including the repetitions. We applied a standard deviation of 5 to the values for species percentages (Table III) and a standard deviation of 7 to the bulk density values of the mixtures (Table V). These values were used after consulting experts from the associated mill. The range of measured CSF values differ slightly for the five mixtures.

Wood species	Mixture 1 (typical)	Mixture 2	Mixture 3	Mixture 4	Mixture 5
Black spruce	80%	90%	70%	75%	85%
Fir	5%	10%	0%	15%	5%
Pine	10%	0%	20%	5%	5%
Hardwood	5%	0%	10%	5%	5%

III. Chip mixtures used in pilot trials.

Species	First experimental measurement (g/cm^3)	Second experimental measurement (g/cm^3)	Average dry basic density used (g/cm^3)
Black spruce	0.421	0.426	0.424
Balsam Fir	0.360	0.348	0.354
Pine	0.410	0.424	0.417
Hardwood	0.496	0.496	0.496

IV. Dry basic density for each species.

Mixture	First experimental measurement (kg/m3)	Second experimental measurement (kg/m3)	Average dry bulk density used (kg/m^3)
Mixture 1	140.07	138.43	139.25
Mixture 2	135.15	135.30	135.22
Mixture 3	132.65	135.01	133.83
Mixture 4	133.56	133.51	133.53
Mixture 5	135.93	134.25	135.09

V. Dry bulk density for each mixture.

Table VII focuses on the CSF and specific energy values obtained for the first trial and repetition of each mixture, giving an indication of the inherent variability in the process. Such variability is caused by obstructions in the refiner or difficulties in getting the pulp to drop from the outlet, in which case the target CSF value might not be reached for a certain plate gap, and the operator might decrease the plate gap (i.e., increase specific energy) to reach that CSF.

Figure 2 shows the relationship between CSF and specific energy for all five mixtures. For a given CSF value – for example, 100 mL – Mixture 1 seems to expend the least specific energy and Mixture 2 the most. It also can be seen that Mixture 3 could not reach the lower CSF levels.

Figure 3 shows how each mixture reacts to refining at

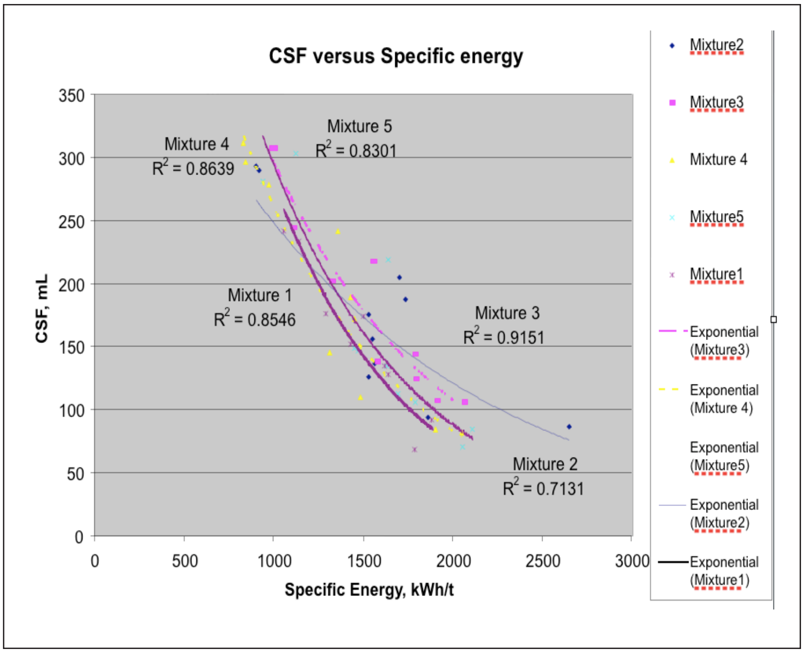
Chip ID	% Black spruce	% Balsam fir	% Pine	% Hardwood	SEC	Bulk density	CSF
1-a	80	4	13	10	1058	140	242
1-b	83	5	9	1	1139	139	234
1-c	79	1	8	3	1292	143	177
1-d	79	2	7	3	1429	140	153
1-e	84	0	5	8	1504	137	175
1-f	79	1	5	8	1622	146	135
1-g	81	3	6	6	1639	138	130
1-h	82	1	6	5	1789	140	69
1-i	77	0	11	3	1883	142	93
1-j	84	2	11	10	2122	144	191
2-a	94	6	1	3	902	137	294
2-b	89	5	1	2	919	136	290
2-c	89	8	2	4	1530	134	127
2-d	89	12	4	5	1533	132	176
2-e	87	8	4	0	1552	134	157
2-f	85	6	1	4	1567	133	137
2-g	87	12	2	1	1705	136	205
2-h	88	13	1	0	1736	130	188
2-i	92	15	0	2	1864	142	94
2-j	93	13	4	5	2651	141	87
3-a	75	2	18	8	991	130	308
3-b	67	2	15	6	1003	138	307
3-c	74	4	18	15	1114	131	245
3-d	67	5	24	11	1326	132	202
3-e	72	2	22	8	1555	128	218
3-f	74	1	21	5	1577	134	138
3-g	67	3	25	7	1792	131	144
3-h	72	4	16	6	1797	130	125
3-i	67	3	24	13	1911	128	108
3-j	71	2	20	15	2066	127	106
4-a	73	18	3	1	829	128	312
4-b	71	20	0	5	844	138	297
4-c	72	20	8	7	972	134	279
4-d	75	13	5	7	1315	140	146
4-e	73	12	3	10	1360	132	242
4-f	79	13	9	0	1431	140	190
4-g	78	10	10	7	1451	133	172
4-h	76	12	2	3	1486	133	110
4-i	78	20	7	6	1905	133	85
4-j	75	18	4	4	2052	133	82
5-a	87	5	9	9	939	133	281
5-b	83	5	0	6	1124	142	304
5-c	80	2	1	10	1452	137	149
5-d	81	4	8	8	1474	136	147
5-e	87	4	5	0	1633	142	135
5-f	83	1	1	9	1642	131	219
5-g	86	1	3	2	1697	141	113
5-h	80	2	7	6	1790	132	107
5-i	81	4	2	5	2057	129	71
5-j	86	0	10	8	2111	142	85

VI. Experimental results of the refining trials for each mixture.

four different plate gap values. No obvious pattern is noticed among the different mixtures. However, the approximate CSF values that can be reached for a given plate gap/specific energy value can be determined for each mixture. This can be quite useful if the chip characteristics obtained from the chip scanner system are known before being fed to the refiner.

SIMULATION MODEL

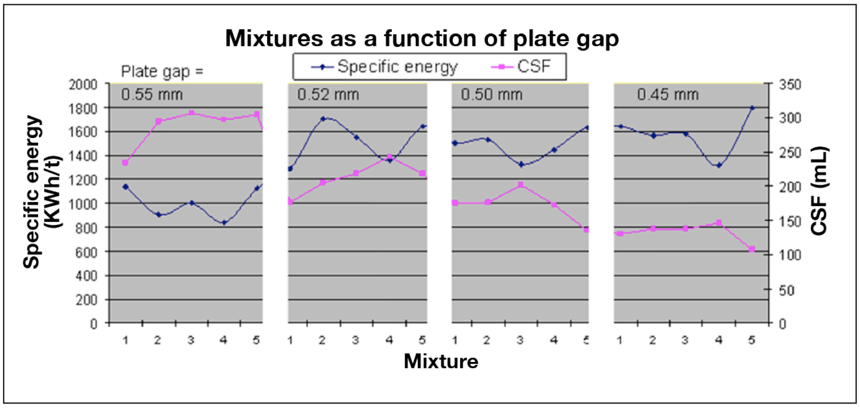
The simulation model consists of two neural network (NN) modules built in the Cadsim Plus process simulation platform [12]. The different simulation steps are labeled in **Fig. 4**. First, for a particular mixture, the values in Table III (species percentage) and Table V (dry bulk density), and mean values of online chip monitor properties (PctDarkChip, hue, saturation, luminance, moisture) are input to the model (point 1). Then, the standard deviations of 5 and 7 are applied to



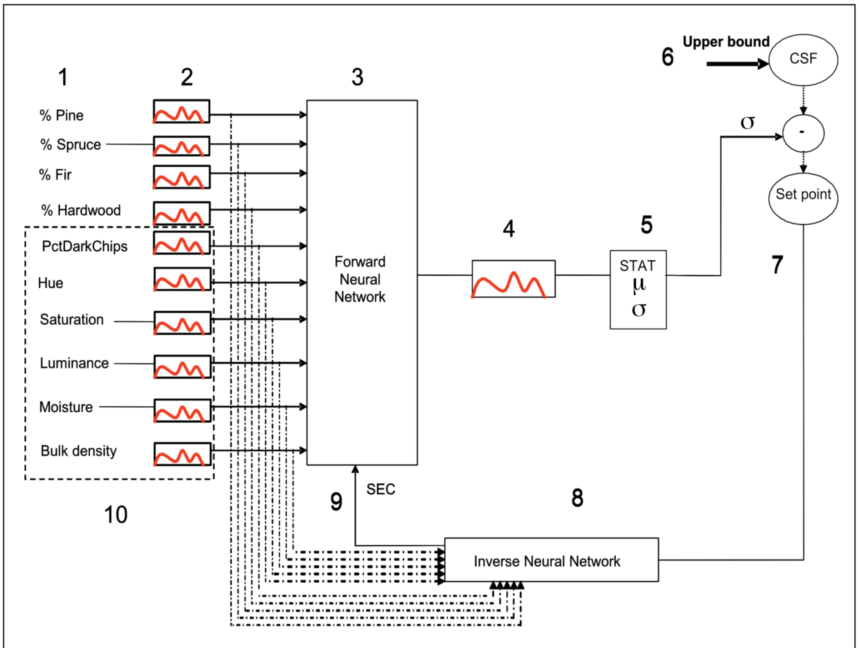
2. Experimental results for CSF as a function of SEC for the five mixtures.

		First trial		Second trial	
		SEC (kW-h/ton)	CSF (mL)	SEC (kW-h/ton)	CSF (mL)
Mixture 1	1	1058	242	1139	234
	2	2122	191	1292	177
	3	1429	153	1504	175
	4	1622	135	1639	130
	5	1883	93	1789	69
Mixture 2	1	902	294	919	290
	2	1705	205	1736	188
	3	1534	176	1553	157
	4	1567	137	1531	127
	5	2651	87	1864	94
Mixture 3	1	1003	307	991	308
	2	1555	218	1114	245
	3	1326	202	1792	144
	4	1577	138	1797	125
	5	2066	106	1911	108
Mixture 4	1	844	297	829	312
	2	1360	242	972	279
	3	1451	172	1431	190
	4	1315	146	1486	110
	5	1905	85	2052	82
Mixture 5	1	939	281	1124	304
	2	1452	149	1642	219
	3	1633	135	1474	147
	4	1697	113	1790	107
	5	2057	71	2111	85

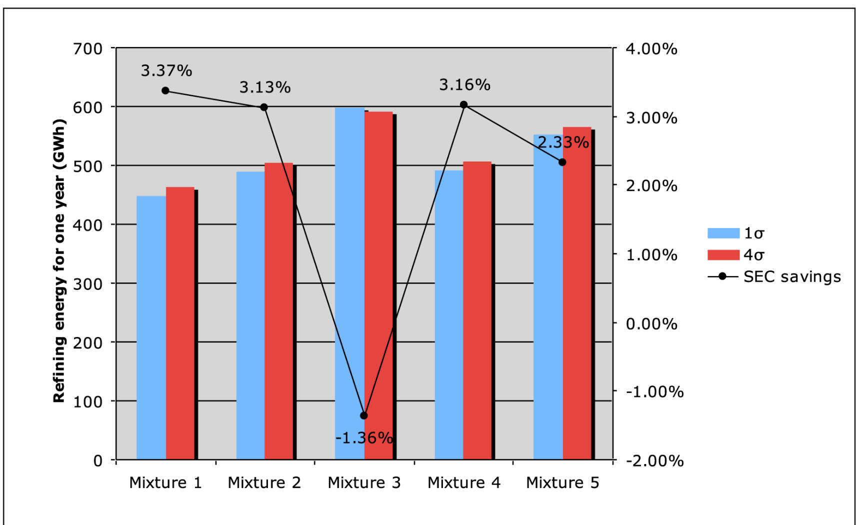
VII. Specific energy and CSF results for each phase of the trials.



3. Behavior of different mixtures as a function of plate gap.



4. Overall structure of the simulation model using random and Dynamic Data Exchange (DDE) data.



5. Simulation results on the effect of chip variability on the potential reduction of annual specific energy.

each species percentage and dry bulk density, respectively, to account for the variability of the mixtures in reality. The variability specified for each chip scanner system property was that of the signals recorded when the chips were scanned by the online chip monitor in the pilot plant. This variability is the standard deviation of 120 chip scanner system continuous measurements taken for each parameter and for each mixture before refining.

As a result a set of random time varying signals (point 2) enters the first NN module (point 3), which computes a CSF prediction (point 4). The statistics of the last 60 CSF predictions are then obtained (point 5). The upper bound for the CSF value is specified as input (point 6). The calculated standard deviation (point 5) is continuously subtracted from this upper bound to generate the new CSF set point (point 7), from which the second NN model (point 8) estimates the new corresponding SEC set point (point 9) to use in production. This new set point is fed back to the first NN module, thus completing the loop.

The production rate used at the pilot plant is about 0.484 kg/min or 0.697 metric tons/day. To compare results with the mill, this rate was increased to 694.4 kg/min or 1000 metric tons/day in the simulation. Usually such an important scale-up would necessitate changes to the initial model. However, SEC is a ratio of motor load over production rate such that pilot SEC is comparable to mill SEC (Table I). For this research, we assumed that this increase in production rate would not affect the results significantly.

Theoretical simulations: effects of chip variability

The set point entering the second NN module is a function of the calculated CSF standard deviation value over the 60 previous simulation iterations. The iteration time step was 1 min, so a new set point is obtained every minute from the statistics of the last production hour. The new CSF set point is computed as follows:

$$CSF_{sp} = CSF_{max} - \sigma_{CSF} \quad \text{(Eq. 1)}$$

where:

CSF_{sp} = Calculated CSF set point, mL

CSF_{max} = CSF upper bound, mL

σ_{CSF} = Standard deviation of the last 60 CSF predictions

Ten simulations were built, two for each mixture: the former used standard deviation values for each input parameter, the latter used these values multiplied by a factor of four as a simple means of increasing variability. With such a factor, the differences in SEC for different variability levels in chip properties could be easily assessed. Each simulation was run a few hours to simulate the results of a whole year of continuous production.

Figure 5 shows the simulation results obtained for each mixture. Mixture 1 required the least SEC, and it saved the most energy annually (3.37% or 46.5 kW-h/ton). The low energy consumption of Mixture 1 can be explained partly by the CSF range obtained: an average of 80% black spruce and 10% pine is a standard composition for producing pulps with CSF in the required 150-200 range (comfort zone). This result supports the use of the Mixture 1 composition at the associated mill. In comparison, Mixture 2 has an average 90% spruce composition. Although pulps produced from this mixture have lower CSF values (i.e., higher quality), they also exhibit higher energy consumption. Still, Mixture 2 shows interesting savings if chip variability is reduced.

Mixture 3 presents losses of 1.36% or 23.8 kW-h/ton. For this particular mixture, the model systematically calculated predictions that were above the specified upper CSF bound. As a consequence, overall annual energy consumption increases were obtained. One of the reasons for this behavior lies in the composition of this mixture: given the lack of spruce and fir and the relatively high proportions of hardwood, the given CSF set point (125 mL in this case) was impossible to reach without additional energy, hence the computed loss.

Validation with mill data: chip density stabilization

The associated mill, with the expertise from Centre de Recherche Industrielle du Québec (CRIQ), proceeded to stabilize the incoming chips' basic density of Mixture 1 to assess the effect of such a control strategy on refining SEC. The partner mill could perform this by dosing the flow of chips coming from three different chip bins, each filled with different chip species. The density of the mixed chips was calculated by the online chip monitor further down the feed line. The measured density value was compared with the set point value and a correction signal was sent back to the appropriate feed screw of the relevant bin to adjust the mixture's composition. The goal was to compare electricity consumption during predetermined periods with and without this feedback control strategy for Mixture 1. A decrease in basic density standard deviation from 11.67 kg/m³ for uncontrolled periods to 7.63 kg/m³ for controlled periods could be achieved through this procedure. This 35% decrease in basic density standard deviation allowed global energy savings of up to 5.0%.

To verify whether the simulation model developed from the pilot plant trials was realistic, data from these mill trials were archived and fed directly to the NN models, using a Dynamic Data Exchange (DDE) protocol. The DDE link is comprised of the PctDarkChip, hue, saturation, luminance, moisture and bulk density signals (the dashed line box labeled point 10 in Fig. 4). The important difference is that in the theoretical simulations, the random variability of these variables might not be physically coherent at each iteration. Even if the random signals are within the prescribed standard deviations, the direction of the change in all chip properties might not be realistic. In theoretical simulations, for example, the saturation and luminance variables can increase simultaneously, whereas in reality they should always vary in opposite directions. In simulations where data are coming directly from the mill via the DDE link, chip properties always vary in a consistent manner.

A total of 1325 lines of mill data for Mixture 1 were used. The simulations converged to a 6.28% or 97.8 kW-h/ton SEC savings for periods when density was stabilized. When compared to the 5% SEC reduction recorded in real mill trials, which included energy losses from the reject refiner not considered in the simulation model, the simulated results are indeed realistic.

CONCLUSIONS

In a context where variations of chip characteristics can cause pulp quality variations of up to 30%, the importance of gathering chip data entering the process cannot be underestimated. Both pilot and mill trials provided interesting results and conclusions.

We observed that chip property variability plays a major role in pulp quality stabilization, in this case CSF. As demonstrated by theoretical simulations and then confirmed by mill trials, chip characteristic variability reduction can reduce CSF variability. The CSF operating set point can be set closer to the upper bound and, as a result, the expected decrease in SEC was confirmed.

Based on theoretical simulations spanning 1 year of continuous pulp production, Mixture 1 requires less energy for a given CSF target. This mixture is representative of the one used by the mill. Mixture 1 also showed the greatest SEC saving when chip characteristic variability was decreased. On the other hand, Mixture 3 consumed the most energy consumption and even caused energy increases, despite a reduction in chip scanner system properties variability. One reason is that the high hardwood content prevented the lower CSF set points from being reached. Another reason is that this trial occurred in a remote region of the NN learning domain, making the general model less accurate for this region.

The associated mill, with the help of CRIQ, obtained 5.0% global SEC savings with 35% reduction in chip density variability. The simulation model developed from experimental results at CIPP was validated using these mill results. A total of 1325 lines of data stored at the mill were used. The simulator could reproduce the decrease in bulk density variability and converged to a SEC saving of 6.28% (or 97.8 kW-h/ton), close to that of the mill trials. This is a good indication that the simulation model could be used for further energy optimization in future work.

These research results show that potential reductions in SEC are possible if wood chip properties, particularly bulk density, are monitored and their variability is stabilized. This is only possible if the mill has the necessary infrastructure to actively control its chip mix in a chip bin control loop that makes use of such chip signals. In another study, the same signals were used in feed-forward control of the refiners themselves [13]. Reductions in SEC also were reported. So far the combined SEC reduction using both chip mixture control and feed-forward refiner control has not been investigated but represents an interesting topic for future research. **TJ**

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INSIGHTS FROM THE AUTHORS

We chose this topic for our research because TMP pulp production consumes massive amounts of energy and this problem needs to be addressed in a sustainable world. In TMP production, variability in pulp quality can come from the process (i.e., the refiners operating parameters) or from the material input (i.e., the chip properties). Previous research has studied the former; in this research, the objective was to study the effect of chip properties using a dedicated apparatus.

Apart from the tedious chip preparation aspects, the most difficult aspect of this study was to validate the simulation models built from the experimental data. Multivariate data analysis was used extensively.

The results of the study showed that controlling chip properties reduces the variability of pulp properties and is therefore an enabler for decreasing SEC. The simulated SEC savings were very close to those recorded by the mill partner. Mills could save energy or increase pulp production rates by considering the use of chip properties monitoring infrastructures.


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The next step would be to combine SEC reduction using chip mixture control with refiner control, where the same signals used in this study can be used in feedforward control of the refiners themselves.

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