Meta-Frontier Data Envelopment Analysis for Performance Improvement of Forest Industry Sub-Sectors in Ontario

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The forest industry sub-sectors in Ontario, which produce a full spectrum of forest products, have been facing extreme competitive pressures due to uncertain demand and supply conditions. This study compares the efficiency frontier of all sub-sectors with the meta-frontier of the entire forest industry in Ontario, using the data envelopment analysis approach. The findings highlight the inefficiency in all the sub-sectors and confirm the existence of different production functions in the industry. This study emphasizes that the efficiency of the relatively inefficient value-added sub-sectors of the forest industry can be improved if specific wood supply policies are designed for them.

Keywords: Data Envelopment Analysis, Intra-Industry Efficiency, Meta-Frontier, Ontario's Forest Industry, Technology Closeness Ratio

1. Introduction

The consumption of natural resources, specifically the forest resources, is vital to an economy's overall development (Hao et al. 2019). Several studies have shown that the changes in the forest industry and economy are closely linked (Stern et al. 1996; Naidoo 2004; Singh et al. 2017). The forest industry in Ontario is an important contributor to the province's economy, and the sub-sectors of the forest industry focus on the production of a variety of products including lumber, pulp, paper and paper products, veneer and composites. However, all of the Ontario's forest industry sub-sectors are currently in a difficult situation (Speers 2010; Canadian Council of Forest Ministers, CCFM 2015). In addition to the cyclical economic recessions, the high-cost and uncertain supply of wood from the forests and the extreme competition from the low-cost competitors in the international market of the forest products has threatened the long-term viability of the Ontario's forest industry sub-sectors (Bullock 2010). These uncertain supply and demand conditions have impacted the relative technical efficiencies of all the forest industry sub-sectors in Ontario. Estimates of the relative technical efficiencies in the Ontario forestry mills have been attempted on an individual basis, for example for sawmills, pulp mills, and paper mills separately (Shahi and Dia 2019, 2020). However, there are no comparisons of the relative technical efficiencies among different sub-sectors of the forest industry, mainly due to the existence of variation in their production technologies. The

variations in the production technologies may exist due to subtle differences in the input attributes or due to the major differences in the final product attributes, and because of the intra-industry heterogeneity.

The forest industry obtains wood supply from the public forests under the provisions of the Crown Forest Sustainability Act (CFSA) 1994, through the forest tenure policy, which defines the pricing system, and the rights and responsibilities for the use of the Ontario's forest resources. The Ontario government's forest tenure policy has been criticized for licensing the wood supply to the large forest companies, with a focus to produce large quantities of low-value commodities (lumber and pulp), and not supporting the value-added forest industry sub-sectors (composites, veneer and paper) (Bogdanski 2008; Harvey and Hillier 1994; Duinker et al. 1991). The forest tenure systems have broad implications for the pursuit of sustainable forest management practices, which define the overarching goal of the forest management policies in Ontario (Haley and Nelson 2007). The government policies related to the forest tenure systems play a major role in determining how the forest industry sub-sectors conduct their business, and consequently impact their relative technical efficiencies (Luckert et al. 2011). However, the forest tenure systems are not sufficiently flexible to accommodate changing economic circumstances and social preferences. On the one hand, new products and technologies are constantly emerging in the forest sector at an accelerating pace, and on the other hand the product markets are subject to cyclical changes in demand and price with changing consumer preferences (Canadian Council of Forest Ministers, CCFM 2015). Several features of the forest tenure systems, such as harvest restrictions and transferability, constrain the ability of forest industry sub-sectors to respond to changing economic and market conditions, thereby having serious efficiency implications (Luckert et al. 2011). The forest industry sub-sectors, especially involved in the value-added production, are unable to make optimum decisions concerning their product mix, input mix, choice of technology, allocation of capital and the markets (Chen and Innes 2013). The government policy regarding the forest tenure systems is supposed to promote each forest industry sub-sector, so that the provincial wood supply is allocated to those mills that can use it most efficiently (Luckert et al. 2011). This will help in the full realization of the economies of scale by rationalizing the manufacturing capacity within different sub-sectors of the forest industry. Therefore, in order to ensure that these government policies are focused in their approach for different forest industry sub-sectors, it becomes inevitable to assess and compare the relative technical efficiency variations among these different sub-sectors.

The relative technical efficiencies of the individual forest industry sub-sectors in Ontario have been analyzed using the data envelopment analysis (DEA) approach, which is a non-parametric linear programming technique (Shahi and Dia 2019, 2020). The advantage of using the DEA approach is that there is no need to explicitly define the production function representing the underlying technology, and can simultaneously consider multiple inputs and outputs (Charnes et al. 1978). Simar and Wilson (1998) advanced the DEA technique by proposing the bootstrapping methodology, which allows the construction of confidence intervals and the generation of robust efficiency scores. The meta-frontier analysis using DEA further differentiates and compares the underlying production technology for each sub-

sector, thereby helping the policy makers in recognizing the need for more focused policies for each sub-sector in the same industry (Hayami and Ruttan 1970, 1971). The meta-frontier analysis emphasizes the heterogeneity of the production technology with different decision-making units (DMUs) in each sub-sector of the industry to reflect the region, type, scale and other inherent attributes (Rao et al. 2003). Each sub-sector of the industry has a different production frontier (called group-frontier), and a broad production frontier (called meta-frontier) is obtained by enveloping the group frontiers of all the sub-sectors (Battese and Rao 2002; Battese et al. 2004). The concept of meta-frontier has been used to study the energy sector, and a few manufacturing and service industries (Assaf et al. 2010; Bhandari and Ray 2012; Lin et al. 2012; Huang et al. 2013; Wang et al. 2013; Zhang et al. 2013; Goyal et al. 2018, 2019). However, there is no past literature to our knowledge that has studied the relative technical efficiency and productivity in the forest industry using meta-frontier analysis.

The general purpose of this paper is to evaluate the relative efficiencies of the sub-sectors of the Ontario's forest industry, in order to direct the government policies specific to the sub-sectors and make performance improvements under uncertain supply and demand conditions. The specific objectives are: (i) to analyze the relative technical efficiencies of the Ontario's forest industry sub-sectors (lumber, pulp, paper, veneer and composites manufacturing), (ii) to plot the Ontario's forest industry sub-sector group frontier vis-à-vis the meta frontier, and (iii) to compare the distance between the local and global frontiers, through the technology closeness ratio, that may arise due to geographical, structural and management factors of the forest industry sub-sectors. This will help focus on the sub-sector specific policies, especially related to forest tenure systems and wood supply in Ontario, on the part of government to target the relatively inefficient sub-sectors of the forest industry. More efficient sub-sectors of the Ontario's forest industry will help in enhancing the market share of the sub-sectors in the global markets.

The rest of the paper is organized as follows. Section 2 provides a literature review of the forest industry and forest policy for wood supply in Ontario, and the application of DEA in the forest industry. Section 3 presents the details of the methodology for DEA, meta-frontier analysis and technology closeness ratio. Section 4 presents the procedure followed for the selection of data and input/output variables. The empirical findings are presented in Section 5. Section 6 provides the managerial insights, and section 7 the concluding remarks.

2. Literature Review

Forests are a major source of wealth for the Canadians, providing a wide range of economic, social and environmental benefits. The forest industry in Canada contributed roughly \$24.6 billion to Canada's economy and accounted for about 7.2% of Canada's total exports (Natural Resources Canada, NRC 2019). Although, the forest industry represents a smaller percentage (about 2%) of Canada's economy, it creates more jobs and contributes more to the balance of trade as compared to other resource sectors (Statistics Canada, 2019). There are two major forest industry manufacturing sub-sectors: (i) solid wood products manufacturing, and (ii) pulp and paper products manufacturing. The solid wood products manufacturing sub-sector is engaged in the production of both primary products (lumber) and secondary products

(veneer, composites and engineered wood products). Whereas, the pulp and paper products manufacturing sub-sector is engaged in the production of a wide range of products, ranging from newsprint and household tissues to dissolving pulp for rayon production (Natural Resources Canada, NRC 2019). The forestry sector is a significant component of the national, provincial and territorial economies, providing jobs and contributing to the high standards of living for the Canadians. Although, the provinces of Ontario and Quebec account for 52% of the total jobs in the forestry sector (Natural Resources Canada, NRC 2019), the long-term viability of the forestry sector in Ontario is threatened by the uncertainty in wood supply due to the forestry tenure issues, and the severe competition in international markets by low-cost competitors. While most of the competitors are producing high-priced value added products, the Ontario companies are still dependent of the primary product markets with shrinking profit margins (Johnson 2015). Moreover, Ontario finds itself in difficult situation because the forest companies in the province have not taken advantage of the new technological opportunities to increase their efficiency and diversify their production (Johnson 2015).

Forest policy in Canada, which reflects the diversity of the forest ecosystems and land ownership, is constantly evolving at the provincial and the national levels. The forest tenure systems, as instruments of the public policy in Canada, define the legislation, regulations, tenure agreements, permits, and government guidelines that outline the rights and the responsibilities of the forest companies to harvest and manage the trees on the public forest lands (Luckert et al. 2011). The forest tenure systems were designed for sustainable utilization and management of the forest resources and for promoting the production of the value-added products (Haley and Luckert 1990). However, the restrictions and provisions of the forest tenure systems not only became a structural and systemic impediment to the production of the value-added products, but also to the protection of Aboriginal and Treaty Rights (Bogdanski 2008). The forest industry, which is already confronted with intense competition from the low-cost producers in the global market place, has been further impacted due to the uncertainty in wood supply because of the faulty forest tenure systems. The economic recessions are further threatening the financial viability of many wood-based businesses. This situation limits the options of investment in the capital and equipment projects, and modernization of the forest mills with the latest technology, thereby impacting their efficiencies.

A few studies have focused on measuring and improving the relative technical efficiencies of the forest industry using data envelopment analysis, which is a non-parametric linear programming based frontier approach (Sowlati 2005; Salehirad and Sowlati 2007; Diaz-Balteiro and Romero 2008; Limaie 2013; Li et al. 2017; and Xue et al. 2018). Shahi and Dia (2019) further improved the application of the DEA in the forest industry by using bootstrap DEA, which allows the construction of confidence intervals and evaluation of robust efficiency scores under uncertainty. They used the bootstrap DEA model for analyzing the relative technical efficiency of 125 sawmills in Ontario, and found low levels of overall technical and managerial efficiencies in the Ontario's sawmills over the entire study period. Shahi and Dia (2020) further used the bootstrap DEA model for analyzing the relative efficiencies of 23 pulp and paper mills in Ontario, and found low levels of relative efficiencies due to the management of operations as well as scale of operations, especially during the

economic downturns. Li et al. (2017) performed DEA analysis to investigate the forestry resources efficiency in 31 inland provinces and municipalities of China. The findings of the study showed that the most dominant factor restraining the forestry resources efficiency was implemented technology. Researchers have also used meta-frontier DEA approach to distinguish between the efficiency scores of sub-groups of the firms on the basis of geographical location, ownership structure and firm characteristics (Battese et al. 2004). The concept of meta-frontier DEA was introduced by Hayami (1969), then expanded by Hayami and Ruttan (1970, 1971) and gradually developed by Rao et al. (2003). The DMUs in the meta-frontier analysis are divided into groups based on the heterogeneity of production technology, and each group forms a production frontier, called a group frontier (Battese and Rao, 2002; Battese et al. 2004). By enveloping the frontiers of different groups, a new production frontier is formed, which is called a meta-frontier. Therefore, the meta-frontier DEA approach has the advantage over the DEA approach that it not only analyzes the efficiencies of the sub-sectors individually, but also compares the efficiencies of the sub-sectors with the overall meta-frontier. The meta-frontier analysis further helps in comparing the distance between the group frontiers and the overall meta-frontier, through the technology closeness ratio. This helps the policy makers in focusing on the sub-sector specific policies and to target the relatively inefficient sub-sectors of the industry. The meta-frontier DEA approach has been used for analyzing and comparing the efficiencies in the sub-sectors of many industries including energy, textile and other manufacturing and service industries (O'Donnell et al. 2008; Assaf et al. 2010; Tiedemann et al. 2011; Bhandari and Ray 2012; Lin et al. 2012; Chiu et al. 2012; Huang et al. 2013; Zhang et al. 2013; Goyal et al. 2018, 2019). However, there are no studies to our knowledge that have used meta-frontier analysis to conduct an in-depth analysis into the efficiencies of the Canadian forest industry sub-sectors. This study is the first of its kind which seeks to fill this gap and enriches the available literature.

3. Methodological Framework

3.1 Data Envelopment Analysis

The CCR model, which estimates the overall technical efficiency (OTE) and assumes constant returns to scale (CRS), was developed by Charnes, Cooper, and Rhodes (Charnes et al. 1978). The dual model of the CCR oriented input is represented as follows:

$$\text{Min} \theta_0 = z_0 - \varepsilon (\sum_{i=1}^m s_i^- + \sum_{r=1}^t s_r^+) \quad (1)$$

$$x_{ij_0} z_0 - \sum_{j=1}^n \lambda_j x_{ij} - s_i^- = 0, i = 1 \dots m \quad (2)$$

$$\sum_{j=1}^n \lambda_j y_{rj} - s_r^+ = y_{rj_0}, r = 1 \dots t \quad (3)$$

Where n is the number of DMUs, t is the number of outputs, m is the number of inputs, x_{ij} is the value of the input s for DMU _{i} , and y_{rj} is the value of the output r for DMU _{i} . The parameters λ_j ($j = 1, \dots, n$) in equations (1) and (2) identify the benchmark DMUs and define an envelope for the evaluated DMU₀. The parameter

θ_0 in equation (1) is the efficiency ratio of the evaluated DMU₀. The parameter z_0 in equations (1) and (2) indicates the proportion of inputs, for an inefficient DMU, needed to produce outputs equivalent to its benchmark DMUs. The parameters s_i^- and s_r^+ in equations (1-3) correspond to the slacks associated with the inputs i and the outputs r , respectively.

The BCC model, which estimates the pure technical efficiency (PTE) and assumes variable returns to scale (VRS), was developed by Banker, Charnes, and Cooper (Banker et al. 1984). The dual of the BCC oriented input model is obtained by adding the following convexity constraint to the equations (1-3):

$$\sum_{j=1}^n \lambda_j = 1 \quad (4)$$

The scale efficiency (SE) can be evaluated as the ratio of the OTE and the PTE as in equation (5). The SE measures the extent by which the overall technical efficiencies can be traced back to the whole operations' scale rather than the management effectiveness and evaluates if the DMU has the optimum scale size and the right amount of resources to operate (Banker et al. 1984).

$$\theta_0^{SE} = \frac{\theta_0^{CCR}}{\theta_0^{BCC}} \quad (5)$$

3.2 Group Frontier and Meta-Frontier

The various sub-sectors of the forest industry (lumber, pulp, paper, veneer, and composites) in Ontario use different production technologies due to the existence of intra-industry heterogeneity. Therefore, the measurement of relative technical efficiencies of the individual DMUs within each sub-sector does not provide a complete picture (Bhandari and Valiyattoor 2016). Rather, a group frontier (also called the local frontier) can be created for each sub-sector. In addition, a meta-frontier (or grand-frontier) can also be created by taking all the sub-sectors of the forest industry together. A particular DMU in a sub-sector can thus be evaluated against these two frontiers, namely, the group frontier or the local frontier vis-à-vis the meta-frontier or the grand frontier.

The existence of different sub-technologies represent different production possibilities that can be used in various sub-sectors of the forest industry (O'Donnell et al. 2008). The DMUs in each sub-sector are categorized based on the output (lumber, pulp, paper, veneer, and composites) produced. Suppose there are n DMUs in the entire forest industry in Ontario that are being observed, such that $j = 1, 2, \dots, n$. Further these DMUs are classified into h number of distinct groups (sub-sectors), where g^{th} group containing n_g number of DMUs, such that (Goyal et al. 2019)

$$n = \sum_{g=1}^h n_g \quad (6)$$

The DMUs are partitioned into non-overlapping sub-sectors such that $J_g = \{j: DMU, j \text{ belongs to the group } g; g=(1, 2, \dots, h)\}$

The production possibility set of the BCC model for the group g is given by

$$T^g = \left\{ (x, y) : x \geq \sum_{j \in J_g} \lambda_{gj} x_g^j ; y \geq \sum_{j \in J_g} \lambda_{gj} y_g^j ; \sum_{j \in J_g} \lambda_{gj} = 1 ; \lambda_{gj} \geq 0 ; g = 1, 2, \dots, h ; j = 1, 2, \dots, n_g \right\} \quad (7)$$

Where, the set T^g represents the production possibility from the observed input-output bundles of the DMUs in a sample of n_g DMUs in the data. The within-group technical efficiency (TE_g) of DMU k (belonging to group g) is obtained using the input-oriented CCR model specified in equation (8), subject to the constraints in equations (9) to (11). The linear programming problem is solved for each DMU k in g^{th} group.

$$\text{Minimize } TE_g^k = \theta_g^k ; \quad (8)$$

$$\text{Subject to: } \sum_{j \in J_g} \lambda_{gj} x_g^j \leq \theta_g^k x_g^k ; \quad g=1, \dots, h ; j=1, \dots, n ; k=1, \dots, n_g \quad (9)$$

$$\sum_{j \in J_g} \lambda_{gj} y_g^j \geq y_g^k ; \quad g=1, \dots, h ; j=1, \dots, n ; k=1, \dots, n_g \quad (10)$$

$$\lambda_{gj} \geq 0 ; \quad g=1, \dots, h ; j=1, \dots, n \quad (11)$$

If we assume the VRS assumption, an extra convexity constraint $\sum_{j \in J_g} \lambda_{gj} = 1$ will be added to the above linear programming problem in equation (8) to (11).

The meta-frontier is the outer envelope of all of the group frontiers. It consists of the boundary points of the group frontiers of the input-output vector of all DMU in the sample. The grand technical efficiency (TE_G) of the DMU k of g^{th} group is obtained by solving the linear program problem in equation (12), subject to the constraints in equations (13) to (15).

$$\text{Minimize } TE_G^k = \theta_G^k ; \quad (12)$$

$$\text{Subject to } \sum_{g=1}^h \sum_{j \in J_g} \lambda_{gj} x_g^j \leq \theta_G^k x_g^k ; g=1, \dots, h ; j=1, \dots, n ; k=1, \dots, n_g \quad (13)$$

$$\sum_{g=1}^h \sum_{j \in J_g} \lambda_{gj} y_g^j \geq y_g^k ; \quad g=1, \dots, h ; j=1, \dots, n ; k=1, \dots, n_g \quad (14)$$

$$\lambda_{gj} \geq 0 ; \quad g=(1, \dots, h) ; j=1, \dots, n \quad (15)$$

If we assume the VRS assumption, an extra convexity constraint $\sum_{g=1}^h \sum_{j \in J_g} \lambda_{gj} = 1$ will be added to the above linear programming problem in equation (12) to (15). The meta-frontier envelopes each group's production possibility set.

3.3 Technology Closeness Ratio

The technology closeness ratio (TCR), measures the proximity of group frontiers to the meta-frontier. A high value of TCR for any group implies that on an average the maximum output produced from the inputs within a group (sub-sector of the forest industry) is close to the maximum output produced from the inputs of the entire

forest industry. In order to assess the proximity of the group frontier to the meta-frontier, we first define an average technical efficiency of the firm in the group as the geometric average of the individual technical efficiencies. For example for the group g , the geometric mean of the individual technical efficiencies is as specified in equation (16), and the geometric mean of the technical efficiencies of group g , measured from the meta-frontier is as specified in equation (17) (Goyal et al. 2019).

$$TE_g(g) = \left(\prod_{k=1}^{n_g} TE_g^k \right)^{1/n_g} \quad (16)$$

$$TE_G(g) = \left(\prod_{k=1}^{n_g} TE_G^k \right)^{1/n_g} \quad (17)$$

The TCR, which is an overall measure of proximity of the group frontier to the meta-frontier, is defined in equation (18).

$$TCR(g) = \frac{TE_G(g)}{TE_g(g)} \quad (18)$$

The group frontiers always lie below the meta-frontier. That means that individual DMUs belonging to a specific group may be quite efficient within the group, but the efficiency decreases when the comparison is made including all the DMUs in the analysis.

4. Description of Data

The choice of inputs and outputs variables has an important influence on the results obtained from the DEA model. Based on the literature review, we found that the most common inputs used in different forest industry sub-sectors include round wood, other wood fibre and labor (Shahi and Dia, 2019). The output depends on the specific forest industry sub-sector. For example, lumber, chips and sawdust are produced in sawmills, different grades of pulp and paper are produced in pulp and paper mills, composite boards and veneers are produced in value-added forest products sub-sectors. In addition chips and hog fuels are produced from all sub-sectors of the forest products industry. In this study, consistent with the choice of inputs-outputs in the literature review, the inputs data include annual round wood and other fibre consumption in cubic meters, and the number of employees, whereas the outputs data includes the product (lumber, composites and veneer in cubic meters, and pulp and paper in metric tonnes), round wood shipped to other facilities in cubic meters, chips and hog fuel shipped to other facilities in cubic meters, and bark and sawdust produced in cubic meters.

There are variations in the production technologies of the different sub-sectors of the forest industry due to differences in the input attributes, and due to major differences in the final product attributes. Therefore, for the purpose of comparison of the relative technical efficiencies among different manufacturing sub-sectors of the forest industry, all the inputs and outputs, except for employees, were converted into dollar value and aggregated together. We used the average cost of inputs (\$55/ cubic meters for round wood and \$35/ cubic meters for other fibre consumption), and

the average price of outputs (\$490 per thousand board feet for lumber, \$600 per metric ton for pulp, \$700 per metric ton for paper, \$400 per thousand square feet for composites, \$450 per thousand square feet for veneer, \$30 per cubic meter for round wood shipped to other facilities, \$25 per cubic meter for chips and hog fuel shipped to other facilities, and \$20 per cubic meter for bark and sawdust produced) as the latest data obtained in discussion with mill managers. The descriptive statistical measures of the inputs and the outputs aggregated data for the five sub-sectors of the forest industry in Ontario are shown in Table 1. The largest average consumption of round wood in terms of value is in the pulp industry sub-sector, whereas the paper industry sub-sector employs the largest average number of employees, and produces the largest value of output. There is very little consumption of round wood and employment provided by the value-added sector, which is against the mandate of the wood supply forest tenure policies.

Table 1 *Descriptive Statistical Measures of the Inputs and Outputs for the Forest Industry Sub-Sectors in Ontario*

Sub-sector		Round wood (\$ million)	Number of Employees	Output (\$ million)
Lumber	#	1402	1402	1402
	Mean	7.04	60.04	13.12
	Median	0.81	18.00	1.65
	Std Dev	12.85	86.18	25.08
Pulp	#	164	164	164
	Mean	47.98	406.69	121.11
	Median	41.80	347.00	100.49
	Std Dev	45.25	377.89	94.73
Paper	#	62	62	62
	Mean	24.39	509.68	135.08
	Median	25.87	446.00	137.89
	Std Dev	9.89	166.58	51.98
Composites	#	112	112	112
	Mean	26.81	142.42	114.43
	Median	21.06	155.00	86.67
	Std Dev	21.54	43.92	82.68
Veneer	#	76	76	76
	Mean	4.53	202.98	16.58
	Median	3.88	219.00	12.45
	Std Dev	3.99	111.21	17.02
Total	#	1816	1816	1816
	Mean	12.46	117.76	33.43
	Median	1.51	31.00	3.35
	Std Dev	22.37	189.27	59.96

The annual data of the inputs and outputs variables for this study were obtained from the Ontario Ministry of Natural Resources and Forestry (OMNRF) for a period of 17 years (1999 to 2015). The data included inputs and outputs of 125 sawmills (with 1402 sample data observations), 15 pulp mills (with 164 sample data

observations), 8 paper mills (with 62 sample data observations), 13 composite mills (with 112 sample data observations), and 9 veneer mills (with 76 sample data observations). The distribution of the DMUs in the sub-sectors of the forest industry in Ontario is shown in Table 2. The data in Table 2 indicates that the majority of the mills in the forest industry in Ontario are sawmills, and that very little attention has been given to promote the value-added sector in the industry.

Table 2 *Distribution of Mills and DMUs in the Sub-Sectors of the Forest Industry in Ontario*

Sub-sector of Industry	No. of Mills	Percentage of Mills	No. of DMUs	Percentage of DMUs
Lumber	125	74	1402	77
Pulp	15	9	164	9
Paper	8	4	62	4
Composites	13	8	112	6
Veneer	9	5	76	4

5. Empirical Findings

5.1 DEA Efficiencies

The facility-wise results of the regular and bootstrap DEA models applied to the full sample of data are presented in Table 3. The results show the bootstrap efficiencies and the regular efficiencies for all the sub-sectors of the forest industry in Ontario. The PTE and OTE efficiencies of the paper mills sub-sector are found to be higher as compared to all other sub-sectors of the forest industry in Ontario (Table 3). Whereas the SE of the lumber mills is higher as compared to the other sub-sectors of the forest industry in Ontario (Table 3). That means the paper mills are doing well with respect to the technical issues, whereas the lumber mills are performing better with respect to the scale issues. The results also show that the pulp mills have the lowest efficiencies as compared to the other sub-sectors of the forest industry, clearly indicating the reason for the pulp mill closures during the study period. Table 4 also shows that most of the mills in the forest industry sub-sectors have low levels of efficiencies, clearly indicating that all the sub-sectors of the forest industry have not been performing well during the study period.

Table 3 *Descriptive Statistical Measures of the Efficiencies Obtained from Bootstrap DEA Models*

Sub-sector		PTE		OTE		Scale Efficiency
		Regular	Bootstrap	Regular	Bootstrap	
Lumber	#	1402	1402	1402	1402	1402
	Mean	0.55	0.54	0.53	0.53	0.98
	Median	0.49	0.47	0.47	0.46	0.99
	Std Dev	0.17	0.16	0.16	0.16	0.08
Pulp	#	164	164	164	164	164
	Mean	0.38	0.30	0.07	0.05	0.21
	Median	0.33	0.26	0.03	0.02	0.12

	Std Dev	0.24	0.17	0.11	0.08	0.24
Paper	#	62	62	62	62	62
	Mean	0.83	0.79	0.68	0.65	0.82
	Median	0.85	0.83	0.67	0.64	0.87
	Std Dev	0.15	0.14	0.18	0.17	0.17
Composites	#	112	112	112	112	112
	Mean	0.76	0.72	0.68	0.66	0.89
	Median	0.79	0.75	0.71	0.70	0.90
	Std Dev	0.16	0.15	0.18	0.17	0.13
Veneer	#	76	76	76	76	76
	Mean	0.60	0.55	0.57	0.55	0.95
	Median	0.63	0.57	0.59	0.56	0.99
	Std Dev	0.22	0.18	0.21	0.20	0.12
Total	#	1816	1816	1816	1816	1816
	Mean	0.17	0.15	0.03	0.02	0.35
	Median	0.09	0.08	0.02	0.01	0.21
	Std Dev	0.21	0.17	0.04	0.03	0.32

The frequency distribution of the regular (PTE, OTE and SE) and bootstrap (PTE and OTE) efficiencies are presented in Table 4. For the purposes of benchmarking, we use the mills in each sub-sector having efficiency in the range of 0.99 to 1.00 (Table 4). We find that a total of 36 lumber DMUs, 11 pulp DMUs, 16 paper DMUs, 9 composites DMUs, and 4 veneer DMUs are PTE-efficient. Whereas, a total of 3 lumber DMUs, 1 pulp DMUs, 4 paper DMUs, 4 composites DMUs, and 1 veneer DMUs are OTE-efficient. We also find that a total of 1215 lumber DMUs, 1 pulp DMUs, 6 paper DMUs, 16 composites DMUs, and 37 veneer DMUs are SE-efficient. These efficient DMUs form the efficiency frontier in the sample, which the inefficient DMU should target to improve their efficiency. The efficient mills represent the best practices of the DMUs in the forest industry and provide managerial insights on how the inefficient ones can improve their efficiencies.

Each sub-sector of the forest industry has a different frequency distribution of the relative efficiencies (Table 4), and as such a different group frontier. For example, more than 50% of the mills in the lumber industry sub-sector fall below an efficiency (PTE and OTE) of 0.5, more than 50% of the pulp mills fall below an efficiency (PTE and OTE) of 0.4, more than 50% of the paper mills fall below an efficiency (PTE and OTE) of 0.9, more than 50% of the composites mills fall below an efficiency (PTE and OTE) of 0.8, and more than 50% of the veneer mills fall below an efficiency (PTE and OTE) of 0.7. This is because different sub-sectors of the forest industry face different production functions. However, the meta-frontier of all the forest industry sub-sectors envelope all the group frontiers representing different sub-sectors of industry.

Table 4 Frequency Distribution of the Efficiencies Obtained from Bootstrap DEA Models

Sub-Sector		PTE				OTE				Scale Efficiency	
		Regular		Bootstrap		Regular		Bootstrap		Number	%
		Number	%	Number	%	Number	%	Number	%		
Lumber	Score < 0.4	228	16.26	274	19.54	256	18.26	301	21.47	7	0.50
	0.4 – 0.5	512	36.52	520	37.09	529	37.73	509	36.31	8	0.57
	0.5 – 0.6	205	14.62	172	12.27	185	13.20	174	12.41	5	0.36
	0.6 – 0.7	139	9.91	142	10.13	142	10.13	137	9.77	7	0.50
	0.7 – 0.8	160	11.41	167	11.91	169	12.05	181	12.91	22	1.57
	0.8 – 0.9	102	7.28	93	6.63	107	7.63	91	6.49	30	2.14
	0.9 – 0.99	20	1.43	34	2.43	11	0.79	9	0.64	108	7.70
	0.99 – 1.00	36	2.57	0	0.00	3	0.21	0	0.00	1215	86.66
Pulp	Score < 0.4	107	65.24	129	78.66	161	98.17	162	98.78	135	82.32
	0.4 – 0.5	20	12.20	12	7.32	1	0.61	1	0.61	10	6.10
	0.5 – 0.6	12	7.32	12	7.32	1	0.61	0	0.00	3	1.83
	0.6 – 0.7	7	4.27	6	3.66	0	0.00	0	0.00	0	0.00
	0.7 – 0.8	4	2.44	4	2.44	0	0.00	1	0.61	3	1.83
	0.8 – 0.9	1	0.61	1	0.61	0	0.00	0	0.00	7	4.27
	0.9 – 0.99	2	1.22	0	0.00	0	0.00	0	0.00	5	3.05
	0.99 – 1.00	11	6.71	0	0.00	1	0.61	0	0.00	1	0.61
Paper	Score < 0.4	0	0.00	0	0.00	2	3.23	2	3.23	2	3.23
	0.4 – 0.5	0	0.00	1	1.61	2	3.23	6	9.68	0	0.00
	0.5 – 0.6	6	9.68	9	14.52	19	30.65	21	33.87	1	1.61
	0.6 – 0.7	6	9.68	5	8.06	12	19.35	14	22.58	10	16.13
	0.7 – 0.8	11	17.74	14	22.58	10	16.13	6	9.68	7	11.29
	0.8 – 0.9	15	24.19	18	29.03	9	14.52	8	12.90	18	29.03
	0.9 – 0.99	8	12.90	15	24.19	4	6.45	5	8.06	18	29.03
	0.99 – 1.00	16	25.81	0	0.00	4	6.45	0	0.00	6	9.68
Composites	Score < 0.4	5	4.46	6	5.36	9	8.04	9	8.04	2	1.79
	0.4 – 0.5	3	2.68	6	5.36	6	5.36	10	8.93	3	2.68
	0.5 – 0.6	10	8.93	10	8.93	14	12.50	12	10.71	1	0.89
	0.6 – 0.7	14	12.50	21	18.75	24	21.43	26	23.21	0	0.00
	0.7 – 0.8	27	24.11	31	27.68	36	32.14	35	31.25	2	1.79
	0.8 – 0.9	31	27.68	30	26.79	15	13.39	15	13.39	52	46.43
	0.9 – 0.99	13	11.61	8	7.14	4	3.57	5	4.46	36	32.14
	0.99 – 1.00	9	8.04	0	0.00	4	3.57	0	0.00	16	14.29
Veneer	Score < 0.4	21	27.63	23	30.26	25	32.89	25	32.89	0	0.00

	0.4 – 0.5	6	7.89	8	10.53	5	6.58	8	10.53	3	3.95
	0.5 – 0.6	9	11.84	12	15.79	8	10.53	8	10.53	0	0.00
	0.6 – 0.7	12	15.79	13	17.11	14	18.42	15	19.74	2	2.63
	0.7 – 0.8	14	18.42	15	19.74	14	18.42	13	17.11	1	1.32
	0.8 – 0.9	5	6.58	5	6.58	5	6.58	5	6.58	2	2.63
	0.9 – 0.99	5	6.58	0	0.00	4	5.26	2	2.63	31	40.79
	0.99 – 1.00	4	5.26	0	0.00	1	1.32	0	0.00	37	48.68
Total	Score < 0.4	1614	88.88	1661	91.46	1812	99.78	1814	99.89	1216	66.96
	0.4 – 0.5	44	2.42	64	3.52	2	0.11	1	0.06	117	6.44
	0.5 – 0.6	60	3.30	38	2.09	1	0.06	0	0.00	61	3.36
	0.6 – 0.7	19	1.05	17	0.94	0	0.00	0	0.00	71	3.91
	0.7 – 0.8	18	0.99	8	0.44	0	0.00	1	0.06	60	3.30
	0.8 – 0.9	14	0.77	6	0.33	0	0.00	0	0.00	63	3.47
	0.9 – 0.99	6	0.33	22	1.21	0	0.00	0	0.00	133	7.32
	0.99 – 1.00	41	2.26	0	0.00	1	0.06	0	0.00	95	5.23

5.2 Group Frontier vis-à-vis Meta-Frontier

The meta-frontier of the entire forest industry in Ontario and the group frontiers of the sub-sectors are plotted together in Figure 1. The inputs and outputs have been aggregated together for representation in a two-dimensional space (Figure 1). As is evident, different sub-sectors of the forest industry face different production functions. Although, the meta-frontier envelopes all the group frontiers representing different sub-sectors of the industry, the meta-frontier alone does not provide a complete picture of the sub-sectors of the forest industry in Ontario. A comparison with the individual group frontiers provides a better comparison of the intra-sub-sector efficiency comparison of the forest industry in Ontario. It can be seen from Figure 1 that the group frontier of the pulp sub-sector is closest to the Meta frontier of the entire forest industry, and the group frontier of the veneer sub-sector is farthest from the Meta frontier of the entire forest industry in Ontario. This clearly indicates that in the intra-sub-sector efficiency comparison, the pulp sub-sector performs better than the rest. This is because most of the forest tenure policies have been framed keeping the pulp sub-sector in mind, thereby completely ignoring the value-added forest products sub-sector of the industry.

Figure 1 Meta-Frontier of the Forest Industry and Group Frontier of Sub-Sectors Dotted line is for the Constant Returns to Scale (CRS) Technology

The individual group frontiers are also plotted separately for each sub-sector of the forest industry in Figure 2. The individual sub-sector group frontiers show that very few firms are operating efficiently within each sub-sector, and the rest of the firms should try to target those efficient firms for improving their technical and managerial efficiencies. The comparison of the efficiency of the DMUs in different sub-sectors of the forest industry can only be done through the meta-frontier analysis (Figure 1), which helps in identifying the technological gaps in the sub-sectors.

Figure 2 Individual Group Frontiers of the Forest Industry Sub-Sectors Dotted line is for the Constant Returns to Scale (CRS) Technology

5.3 Technology Closeness Ration (TCR)

The TCR measures the distance between the group frontiers of different forest industry sub-sectors and meta-frontier of the entire forest industry. The TCR of any group is an index of the proximity of the group frontier to the meta-frontier. A high value of the TCR means that the group frontier of the sub-sector is located close to the meta-frontier of the entire forest industry, and is utilizing its inputs more efficiently than other sub-sectors of the forest industry.

The TCR based on the PTE, OTE and SE scores of different sub-sectors of the forest industry in Ontario measured from the group frontiers against the meta-frontier are summarized in Table 5. The rank of the TCR indicates which sub-sector of the forest industry is closest to the meta-frontier of the industry. The results of TCR ranking in Table 5 clearly show that the pulp industry group frontier is ranked the highest, and is the closest to the meta-frontier of the entire forest products industry in Ontario. That means the pulp sub-sector is utilizing its inputs more efficiently than other sub-sectors of the forest industry. All other sub-sectors are inefficiently using their inputs in the forest industry of Ontario. For example, for the lumber mills the TCR value based on the PTE is 0.18, based on OTE is 0.19, and based on SE is 0.10.

The low TCR ratios indicate that there is gap in the performance of the lumber mills with respect to the overall forest industry performance. The lumber mills are ranked second for the PTE and OTE, and fourth for the scale efficiencies. The gap in TCR for the lumber mills can be reduced by eliminating the managerial and technical inefficiencies, or by expanding the scale of operations of the sawmills in Ontario. The value-added sub-sectors (paper, composites and veneer) of the forest industry in Ontario are ranked the lowest for different efficiencies (Table 5). That means the value-added sector is not utilizing its inputs to the full potential, either due to technological issues or scale issues. The value-added wood based (composite and veneer) sub-sectors of the forest industry are ranked third and fourth for different efficiencies, indicating there is a scope for improvement in both the managerial and technical efficiencies, as well as scale efficiency for this sub-sector. However, the paper mills sub-sectors has the second rank for the scale efficiency, but fifth rank for the PTE and OTE. That means the paper industry needs to focus on the managerial and technical issues of efficiently utilizing their inputs, and not so much on the scale issues.

Table 5 *Technology Closeness Ratio (TCR) of the Forest Industry Sub-Sectors*

Sub- sector	PTE				OTE				Scale Efficiency	
	Regular		Bootstrap		Regular		Bootstrap			
	TCR	Rank	TCR	Rank	TCR	Rank	TCR	Rank	TCR	Rank
Lumber	0.18	2	0.18	3	0.19	2	0.19	2	0.10	4
Pulp	0.30	1	0.39	1	0.97	1	0.99	1	0.71	1
Paper	0.12	5	0.12	5	0.14	5	0.15	3	0.12	2
Composites	0.13	4	0.14	4	0.15	4	0.15	3	0.11	3
Veneer	0.17	3	0.19	2	0.18	3	0.19	2	0.10	4

6. Managerial Insights

The local and global frontiers of the forest industry sub-sectors in Ontario, evaluated using data envelopment analysis, compare the relative efficiencies of different sub-sectors of the forest industry, under uncertain demand and supply conditions. The uncertain demand conditions are created due to the competition from low-cost producers in the global markets, and the uncertain supply conditions are created due to the restrictions in the forest tenure policies. The results of this study, which show very low relative efficiencies of the value-added forest products sub-sectors (with more than 50% of the composites mills having less than 0.8 efficiency, and more than 50% of the veneer mills having less than 0.7 efficiency), clearly indicate that the forest tenure policies should reduce the uncertainty around wood supply and promote the production of value-added forest products for the performance improvement of the entire forest products industry in Ontario.

Earlier studies evaluating the performance of individual sub-sectors of the forest industry in Ontario using data envelopment analysis found that the economic downturns in global markets have resulted in several challenges with mill closures and reduced production (Shahi and Dia, 2019 and 2020). The results of this study

clearly indicate that the source of operational inefficiency in all sub-sectors of the forest industry in Ontario has been both due to the managerial and the scale issues. This has resulted in the inputs not being efficiently utilized in all sub-sectors of the forest industry in Ontario. Therefore, the policy makers and industry stakeholders should focus their attention on improving the operational efficiency and the competitiveness of Ontario's forest industry through streamlining manufacturing processes, reducing costs, improving raw material usage, and making capital investments in the new and improved technology.

The results of our study also indicates that the value-added sector, which has very low relative efficiencies as compared to the primary commodity sector, presents new opportunities for the forest products industry for better utilization of inputs. This is because the primary commodity sector depends on the US housing industry for lumber and global paper and paper-products sector for pulp. The collapse of the US housing industry and the disruption of the fiber supply chains in the pulp sector has further impacted their efficiencies, resulting in a number of mill closures and reduced production. In order to promote the value-added forest industry sub-sectors, it is important that knowledge is continuously developed, transferred, and adapted by the forest products industry in this sub-sector. This requires a close working relationship of the forest products industry with academia and research organizations through research projects, continuous training, and workshops. The forest industry in Ontario should make use of the operational and tactical decision-support tools that monitor the manufacturing processes and provide process control information to improve their strategic decision-making.

The benchmarking of efficient mills with high efficiency scores helps managers understand the best practices in each sub-sector of the forest industry and provides managerial insights into how inefficient mills can improve their efficiencies by benchmarking and identifying internal opportunities for improvement. By studying mills with superior performance, breaking down what makes such superior performance possible, and then comparing the processes of those mills, an inefficient mill can implement changes that will yield significant improvements. The inefficient mills in each sub-sector can improve their efficiencies either by decreasing their inputs or by increasing their outputs. The efficient mills help managers in further setting goals for the technology and productivity changes. The new and emerging technologies and business processes offer innovative ways of generating social and economic values from the inputs in the mills. These new technologies and business processes also help in adding new revenue streams from inputs, diversifying product lines, and boosting the share of products in the marketplace. Benchmarking also enhances the familiarity of the employees with the key performance metrics and opportunities for continuous improvement in the mills.

Finally, the results of the technology closeness ratio for the different sub-sectors of the forest products industry in Ontario indicate that each sub-sector faces a different production function. The results also indicate that the value-added sub-sectors of the forest industry in Ontario have the lowest technology closeness ratio (0.10 to 0.19). That means the value-added sector is not utilizing its inputs to the full potential, either due to the technological issues or the scale issues. The best way to promote the value-added sub-sectors in the forest products industry is to develop a cluster of industries, where the output of one sub-sector can be fully utilized as inputs to other

sub-sectors of the industry. There is no forest industry cluster in Ontario at present, although past research has also confirmed that the performance of the forest industry can be substantially improved by promoting the concept of a forest industry cluster.

The results of our study provide useful insights for the policy makers and the mill management, so that future resources can be reallocated to improve the performance of different sub-sectors of the forest industry in Ontario. However, the DEA methodology has some limitations for benchmarking purposes. The DEA methodology may inappropriately screen out candidates from benchmarking with a relative efficiency score of less than 1, based on the combinations of inputs and outputs specified. This may result in a DMU not being selected as a benchmark while performing well otherwise with respect to the overall inputs and outputs. Therefore, the results of the relative efficiencies from this study should be considered along with the performance measurement of some key financial performance indicators in the decision-making process.

7. Conclusion

Ontario forest products industry mainly focuses on the production of low-value primary commodity products such as lumber and pulp, and has not been able to promote the secondary value-added forest products sub-sector such as composites, veneer and paper products. The lumber and pulp sub-sectors of the forest products industry in Ontario have not done well and have been facing extreme competitive pressures in the global market from low-cost producers due to the reduced demand and uncertain wood supply conditions. The forest products industry has further suffered due to the economic downturns and cyclical variations in the global markets.

In this study, the relative efficiencies of the sub-sectors of the Ontario's forest industry were evaluated together by comparing the group frontier of the sub-sectors with the meta-frontier of the entire forest industry, using the DEA approach. This is the first study, which has compared the relative efficiencies of the sub-sectors of the forest industry in Ontario together. It is evident that the value-added sub-sector of the forest industry is not performing well as compared to the lumber and pulp sectors. Even the lumber and pulp sectors have low relative efficiencies. The wood supply in Ontario, which is governed by the forest tenure policy, has only focused on the production of commodity products, resulting in lack of competitiveness, whereas the focus should be on the production of value-added products. The low levels of the operational efficiencies suggest that focus of improvement in the mills should be on streamlining the manufacturing processes, reducing costs, improving raw material usage, and making capital investments in the new and improved technology. We suggest the creation of the forest industry cluster for the sustainability of the industry, where the outputs from one sub-sector can be utilized by another sub-sector, resulting in better utilization of the inputs. Moreover, the performance of all the sub-sectors should be continuously evaluated and the knowledge developed in this area is regularly shared with the managers and adapted in the industry for strategic decision-making.

The results of this study highlight the fact that the focus of policy measures should be on improving production in the primary production sub-sectors (lumber and pulp) and promoting value-added sectors (composites, veneer, and a variety of paper

products), and efficiently utilizing inputs by using new and emerging technologies and business processes that offer innovative ways of generating social and economic values from the inputs. Our study is unique in analyzing the performance measures of Ontario's forest industry sub-sectors with respect to comparing their pure technical, overall technical, and scale efficiencies. However, the results of this study are limited by the availability of data for inputs and outputs. More inputs and outputs data would further improve the results of this study.

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