Current Practices in Log Yard Design and Operations in the Province of Quebec, Canada

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Abstract

Log yards play an important role in the forest supply chain by connecting raw material supply to manufacturing processes. Log yard design and operations have not been thoroughly represented in the scientific literature, though research in other industrial sectors has demonstrated the strategic operational importance of warehouses. This article investigates the log yard design and operations in current industrial practices.

An analysis of existing log yards was conducted in Quebec. Detailed information about throughput, equipment, personnel, inventory management, and design considerations was gathered by means of questionnaires, on-site visits, and meetings with yard managers.

The survey of current practices (design, management, and operations) confirms that most existing yards have been designed without a systematic method. Crucial performance inhibitors included log yard shape, in-flow management, and poor surface material. Results point toward a potential gain in competitiveness by improving log yard practices, optimizing log yard shape and layout, better coordinating the forest–mill operations, and enhancing surface material.

Supplying an adequate volume of appropriate raw material at the right time is the key role of log yards (Dramm et al. 2002). Depending on their position in the forest supply chain, log yards may serve other purposes such as wood inventory accumulation, acting as a reloading point, log sorting, raw material preprocessing, and mill in-feed (Dramm et al. 2002). Moreover, log yards are often a decoupling point in separating raw material and semifinished product flows from forecast-driven to customer order–driven production (Christopher and Towill 2001, Lehoux et al. 2012, D'Amours et al. 2016). When log yards function as production and distribution warehouses, they effectively contribute to managing the variability of raw material and controlling the log mix crucial for sawmill operations. Mill log inventories are required to ensure continuous facility production. Consequently, log supply in the yard must be sufficient to keep the mill operating at maximum efficiency at all times (Williston 1976). The accumulation of wood inventory in anticipation of seasonal interruptions in transportation, such as thaws or intense rainfall, is critical to avoid production shutdowns.

A well-planned and efficiently operated log yard can make a significant contribution to a company's overall profitability (Dramm et al. 2004). Ineffective yard management, however, can result in higher costs, loss of value because of wood damage and fiber loss from poor handling, and wood and fiber deterioration because of long storage periods. For example, as quoted in Favreau (2002), 6 percent of fiber loss is reported while debarking dry wood. Inadequate yard management can also increase processing variance because of increased raw material variability (Moore and Cown 2015).

Just as with any warehouse, efficient log yard operations require specific design considerations. The performance of a warehouse's operations is closely related to its design (Gu et al. 2010). Extended truck queues, long travel distances by forwarding machines, equipment cross-flows, and unused space are symptoms of poorly designed warehouses,

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resulting in complex management, poor customer service, and high logistics costs (Van den Berg 2007). Warehouse activities can make between 20 and 50 percent of the supply chain operational costs (Tompkins et al. 2010). Thus, a warehouse should be adequately designed to avoid any unnecessary costs.

Warehouse design problem

Warehouse design consideration is a highly complex task due to multiple interactions between design decisions and their operational subproblems. These decisions and subproblems have been reported in several literature reviews (i.e., Cormier and Gunn 1992; Rouwenhorst et al. 2000; Gu et al. 2007, 2010; da Cunha Reis et al. 2017). For example, Gu et al. (2007) classified the warehouse design problem around five key decisions: general structure, sizing and dimensioning, equipment selection, layout determination, and operation strategy selection. The overall structure defines the material flow within the warehouse, the specifications of functional departments, and their interrelations. Dimensioning determines the size of a warehouse and the distribution of space between various departments. Warehouse layout is a detailed configuration that determines allocation of aisles, storage space, and exits. Determined by the layout, travel distance is often considered a primary objective in warehouse design and optimization. Equipment selection regulates the appropriate level of automation for the warehouse and identifies the equipment for operation. Operation strategy determines how the warehouse will be operated based on receiving, storage, order picking, and shipping activities. To compound the problem, each of these decisions interacts with each other. For example, raw material allocation depends on the order-picking strategy and available space, while the aisle determination depends on equipment characteristics and size of departments, to name a few of these interactions. These design decisions also affect operational-level subproblems, such as equipment assignment or order-picking sequence. A systematic method is required to evaluate warehouse design and operations performance under specific operational conditions (Baker and Canessa 2009).

In the literature, two major approaches for warehouse design have been proposed. The first approach provides optimization-based methods of separate subproblems (i.e., Goh et al. 2001, Lee and Elsayed 2005, Tremblay et al. 2012). The second approach provides a sequential top-down method to organize problem complexity (i.e., Baker and Canessa 2009, Strack and Pochet 2010, Dotoli et al. 2015). To our knowledge, no document proposes a comprehensive approach for warehouse design considering seasonal variation of capacity requirements.

Log yard design problem

The log yard design problem is also characterized by multiple interactions between design and operation-level decisions. Although warehouses and log yards share many design and operation challenges, log yard design must consider the key specifications associated with the forest supply chain. Those include raw material properties (deterioration, breakage, heterogeneity), transport specifications (truck arrival frequency, average load), and divergent processes (bucking, sorting). Design is also influenced by environmental limitations associated with yard location and specific maintenance conditions (e.g., snow removal, debris disposal, water sprinkler system).

Another important issue related to designing a log yard is seasonal inventory fluctuations. According to Thomas and Wallis (1971), seasonality can be defined as ''systematic, but not necessarily regular movements or fluctuations in a period equal to or shorter than one year, which occurs in a time series.'' Seasonal fluctuations require flexible warehouse design and inventory management (Baker 2008). In northern climates, log yard operations are severely impacted by the seasonality of wood supply. Strict restrictions on transport in the form of weight limits or complete bans on heavy loads trucks are imposed in the spring. Important accumulation of raw material in the log yard before the thaw is then required to avoid production shortage at the sawmill (Beaudoin et al. 2012). However, log yards are not affected by the seasonality in the same manner. In this case seasonality depends on various factors, such as the private or public road network and the use of intermediate storage in satellite yards. To investigate the issue of log yard design performance, it is necessary to consider log yard design decisions under the influence of the regional supply conditions.

Log yard design and performance has not been thoroughly reported in the literature. Nevertheless, several documents address separate subproblems related to log yard performance. These include procurement and inventory optimization (Mendoza et al. 1991, LeBel and Carruth 1997, Favreau 2002, Myers and Richards 2003, Hultqvist and Olsson 2004, Alam et al. 2014) and operations improvements (Sedney 1992, Dramm et al. 2002, Deckard et al. 2003, Tran 2009, Beaudoin et al. 2012, Rathke et al. 2013).

With respect to procurement and inventory control, an inventory control model with log input optimization was developed to determine the sawmill's lumber production schedule. LeBel and Carruth (1997) provided a stochastic model to simulate the wood procurement fluctuations to optimize logging capacity and wood inventory. Favreau (2002) presented an economic model to assess the impact of storage duration on procurement costs. Myers and Richards (2003) evaluated the impact of harvesting techniques on length of operating season, inventory handling, and holding costs. Hultqvist and Olsson (2004) addressed the optimization of round wood procurement at a tactical planning level, while Alam et al. (2014) investigated the economic impact of enhanced forest inventory and merchandizing yards on the value recovery in the forest products supply chain.

On the operational side, Sedney (1992) evaluated yard operational feasibility under raw material characteristics and site configurations. Deckard et al. (2003) examined the factors affecting truck cycle time, while Tran (2009) investigated the handling equipment productivity depending on loader type, in-yard distances, height of log piles, and raw material allocation. Beaudoin et al. (2012) evaluated loader-to-truck allocation strategies to minimize truck cycle time and distances traveled by handling equipment. Rathke et al. (2013) presented an integrated approach to minimize the in-yard transportation by considering transportation time, storage capacity, and yard crane deployment.

Several publications address the log yard design issues. Dramm et al. (2002) presented the basic concepts of log sort-yard design and operation characteristics. They highlighted that success for a log yard design depended on minimizing log inventory with clear, well-defined log procurement and proper handling equipment choices. Their literature review also addressed yard location problems, operational rules, economic feasibility, storage and inventory control, protection, and residue disposal. Dramm et al. (2004) completed the foregoing overview with critical factors in log sort-yard feasibility in economics, planning, and construction. Yujie and Fang (2009) studied systematic yard layout planning methods, while Kons et al. (2014) provided a detailed overview of design characteristics, such as surface area, handling equipment, and stored assortments of terminal yards. Recently, Huka and Gronalt (2018) investigated log yard logistics problems with a structural approach, providing practical examples to demonstrate the potential of operational improvement.

Only two authors proposed log yard design methods in the early 1980s. First, Hampton (1981) developed a sequential procedure to design a log yard: (1) data collection of yard resources, (2) raw material flow analysis, (3) determination of required space for each activity, (4) preliminary layout, (5) evaluation of preliminary layout, and (6) evaluation of alternatives. He also provided log yard construction guidelines pertaining to coating structure, pollution control, and maintenance and disposal system. While comprehensive, Hampton's guidelines did not present alternatives for selected log yard capacity (handling equipment) for preliminary designs, nor did he consider the influence of seasonal wood supply conditions on design and performance. Second, Sinclair and Wellburn (1984) proposed a log yard design method by presenting a general overview of log yard design, construction, and operation problems based on space and equipment requirements for each operation. Their method included a detailed financial evaluation of log yard establishment. Nevertheless, since the design problems were considered separately, dynamic interactions between log yard activities were not evaluated.

Recently, Vachon-Robichaud et al. (2014) applied Hampton's method complemented by a simulation technique to evaluate the performance of miscellaneous log yard designs. The authors investigated equipment capacity selection and interactions between yard activities. Their study revealed the opportunities in better product allocation and dynamic examination of equipment capacity according to seasonal supply conditions.

Table 1 reports the number of publications focusing on design and operation problems in warehousing and log yards. Our scan of the literature reveals that several exhaustive reviews specifically focused on warehouse issues. Those articles show that 342 publications have investigated warehouse design and operation problems since 1963. Eighteen research articles have adopted a sequential procedure to develop an efficient design, hence reflecting the importance attributed to efficient design and operations for the supply chain's performance.

In addition, the review highlights the limited emphasis on log yard issues. The number of research articles pertaining to log yard design is mostly limited to operational subproblems. Only three publications dealt with log yard design procedures (Hampton 1981, Sinclair and Wellburn 1984, Vachon-Robichaud et al. 2014). These procedures may serve as a guide for practitioners interested in identifying design problems and improving their yard operations. The procedures, however, did not investigate the log yard design decisions under seasonal supply constraints.

Consequently, we see a gap in the scientific literature with respect to structured design method for log yards under seasonality of log supply, as is the case in eastern Canada.

A more detailed understanding of log yard design issues is required to reliably evaluate their performances. Identified gaps in scientific literature led us to investigate the log yard design and performance in practical environment. Although warehouses yield significant gains when improving design and operations, we presume that improving log yard design has the same potential.

Building on observations, our research aims to develop a log yard design methodology considering seasonal supply variations. As the first step toward that goal, this article investigates crucial factors in log yard design and performance in the province of Quebec. For this purpose, we determined three specific objectives: (1) document characteristics and current practices in design and operations of a large mill yard sample, (2) evaluate the impact of wood supply seasonality on log yard performance, and (3) identify performance inhibitors in log yards' design and operations.

Methods

The characteristics and current practices of log yard design and operations were documented by conducting a mail survey and semistructured interviews. Our project focused more specifically on the log yards associated with softwood sawmills (fir–spruce–pine–larch) in Quebec. A list of 74 fir–spruce–pine–larch sawmills was obtained from the provincial government's database. The database identified mills with production capacity ranging from 2,200 to 980,000 m^3. To comprehensively determine the degree of

Table 1.—Number of publications on design and operation problems and procedures between 1963 and 2018.

Period	Warehouse[a]			Log yard		
	Design problems	Design procedures	Operations	Design problems	Design procedures	Operations
1963–1980	9	2	14	0	0	0
1980–1990	38	1	40	0	2	0
1990–1995	26	3	32	0	0	2
1995–2000	40	2	45	0	0	1
2000–2005	20	7	31	2	0	4
2005–2010	16	2	22	0	0	1
2010–2015	7	1	2	2	1	3
2015–2018	0	0	0	1	0	0

[a] Based on literature reviews in Cormier and Gunn (1992), Rouwenhorst et al. (2000), Gu et al. (2007, 2010), Baker and Canessa (2009), Kostrzewski (2014), Davarzani and Norrman (2015), and da Cunha Reis et al. (2017).

heterogeneity of log yard resources, supplies, and designs of comparable sawmills sizes, we filtered the database to include only operating mills with an annual production capacity exceeding 100,000 m^3 in 2016. Sixty mills matched these criteria.

A questionnaire was developed based on a literature review on yard performance evaluation (Hampton 1981, Sinclair and Wellburn 1984, Gu et al. 2010, Vachon-Robichaud et al. 2014) and personal contacts with handling equipment distributor specialists. The survey consisted of 35 questions (both open-ended and multiple choice) related to log yard area, wood supply characteristics, resources, design constraints, management strategies, and performance perception.

As suggested in the literature (Yu and Cooper 1983, Yammarino et al. 1991), a personalized survey was mailed to each selected mill yard to generate a high response rate. Cover letters were either addressed directly to the log yard managers or to the mill directors. Prior to mailing the survey, we called mill yards to explain the purpose of the research and identify the person best suited to respond to the survey. For each log yard, a preanalysis using photogrammetric information from Google Earth Pro 2016 was conducted. The preanalysis included determination of mill site departments (log yard, semifinished and finished products, and chip storage zones) and estimation of their areas. The respondents were subsequently asked to validate this information in the survey.

The survey was validated using the method proposed by Ketele and Roegiers (2009). First, we ensured that the collected information served the purpose of the investigation. Each relevant question was validated internally with representatives from two handling equipment distributors. The questionnaire was then pretested with a yard manager. We mailed the survey in mid-March 2016. We gave participants two monthly reminders by e-mail and by phone. The completed surveys were gathered until the end of August 2016. Clarification and validation of survey responses were made using follow-up calls, e-mail, and semistructured on-site interviews. Visits and interviews with log yard managers took place from March to July 2017 with a subsample of 10 mill yards having various supply contexts and geographic locations.

Basic information about yards and current practices are reported as percentages, averages, or medians with ranges. The impact of wood supply seasonality on inventory level and the number of yard employees was investigated using the Wilcoxon signed-rank test. Due to the sample size and data distribution, all statistical tests were conducted at a significance level $\alpha = 0.10$ using SAS (version. 9.4; SAS Institute Inc., Cary, North Carolina).

Results and Discussion

The survey response rate was 63.3 percent. The respondents were not significantly different from the nonrespondent group with respect to production capacity (Student's t test, t value 1.3692, P value 0.1763). The number of respondents varies for each question, since some did not answer every question. The answer rate to specific questions varies from 68 to 100 percent. The number of responses (n) is presented for each question along with the results. In the case of multiple answer or open-ended questions, the number of responses can exceed the response rate—38 yards (e.g., number of machines).

Yard characteristics

The average volume handled annually by surveyed yards ranges from 60,000 to 950,000 m^3 over the period from 2011 to 2015. Two yards handled less than 100,000 m^3 annually for the surveyed period. On average, the surveyed log yards handled a combined volume of 14 million m^3 of round wood annually.

Area

The surveyed log yards occupied an area ranging from 1.4 to 58 ha with a median of 17.4 ha (mean of 18.9 ha). Log yard distribution, dependent on area, is presented in Figure 1. Many yards (68.5%) occupy an area $\leq$20 ha. However, these yards represent only 42 percent of the total area because four sites are significantly larger (>40 ha).

The area in surveyed yards is only slightly associated with annual volume, as shown in Figure 2, which suggests the heterogeneity of operational conditions and applied inventory strategies.

Spatial distribution (space arrangement on an industrial site) is an important aspect of log yard area, as it influences the distances for in-yard transport for rolling equipment and can therefore be perceived as a major factor in explaining operational performance. As shown in Figure 3, the surveyed log yards have different shapes. A circular shape with the mill in the middle (compactness index [CI] = 1[1]) could arguably be an optimal shape to reduce equipment movements. A relatively small proportion of log yards are operated within a shape that minimizes the distances (CI: minimum 0.004; mean and median 0.024; maximum 0.052). Most facilities are characterized by nonoptimized shapes, with long in-yard transport distances (up to 1.3 km). These long shapes are mostly the result of expansion over time (due to changing mill production) constrained by local land use and zoning restrictions. In many cases, log yard layout represents a field for considerable design improvement. For yards where optimal shape would be limited by physical and environmental constraints, the in-yard distances should be minimized by adequate allocation of raw material in storage zones.

Space allocation is an important issue no matter the shape of a yard. The surveyed log yards occupied between 20 and 87 percent (median of 46%, mean of 49%) of the total industrial site—the sum of log yard, wood chip storage zone, and lumber yard area, excluding buildings and parking.

Three main types of surface material (including yard roads and storage zones) were identified in surveyed log yards: beaten earth, gravel, and asphalt. The proportions of surface area by type of material in surveyed log yards are presented in Table 2.

Most yards (60.5%) have no asphalt-based pavement. In comparison, in Sweden less than one-third of wood terminals are unpaved, and the rest have from 28 to 60 percent of hard surface (Kons et al. 2014). Only 15.5 percent of log yards have more than 20 percent of their surface asphalted, and the maximal proportion of asphalt reported was 60 percent. Thirty-seven percent of the yards do not operate on beaten earth. In general, beaten earth and gravel surface are the most common (medians of 50% and 35% of yard area, respectively). During on-site visits, we noted that

[1] According to equation: $CI = area/perimeter^2$.

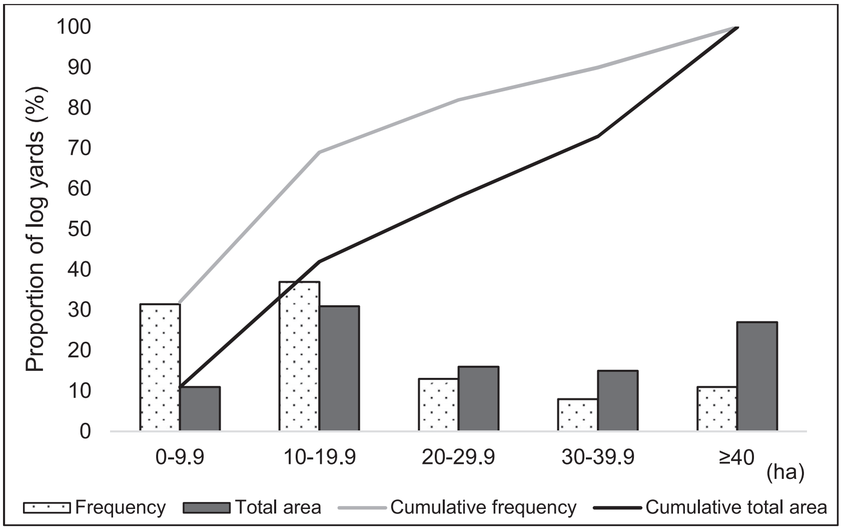

*Figure 1.—Log yard area (*n *= 38).*

asphalt and gravel surfaces in some solid surface proportions were principally used for the roads, while the beaten earth occupied the storage zones.

Design constraints

Log yard design is influenced by specific operational constraints. The respondents were asked to prioritize the most important constraints that have influenced their yard design. Figure 4 presents the constraints reported as influencing log yard design. Information in the bar chart indicates how often a factor was identified as the first, the second, and the third most important.

Site drainage (74%), available space (69%), and residue management (67%) were the most frequently identified limiting factors in log yard design. The high frequency of site drainage and residue management as critical design constraints may result from poor surface coating. Loose bark and wood fiber mixed with surface material must periodically be cleaned up and residues disposed of. This may point toward the potential of hard coating to improve log yard performance.

The lack of space is identified as the most important constraint in log yard design and operations (48%). It may come as a surprise that available space is perceived as a constraint when considering that the average area of log yards is already quite large (18.9 ha). Although statistics for other regions were not found, a nonsystematic survey for other regions in the world points toward smaller yards in similar industries. For example, Sinclair and Wellburn (1984) estimated the yard area on Canada's west coast as being in range of 2 ha for those yards approximately processing 400,000 m^3 annually. Based on 18 visits in log sort yards in the United States, Dramm et al. (2002) reported areas ranging from 0.2 ha—for yards handing less than 60,000 m^3 annually—to 4 ha for the larger yards (more than 240,000 m^3 handled annually). In Sweden, 74 percent of terminal yards have an area less than 2 ha (Kons et al. 2014). However, it appears that these estimations do not consider seasonal

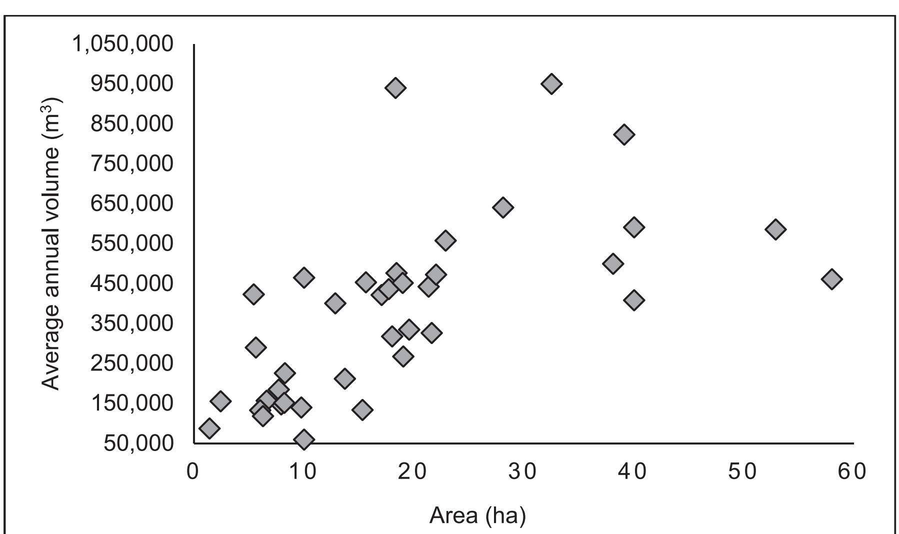

Figure 2.—Average volume handled annually and log yard area for the 38 surveyed yards.

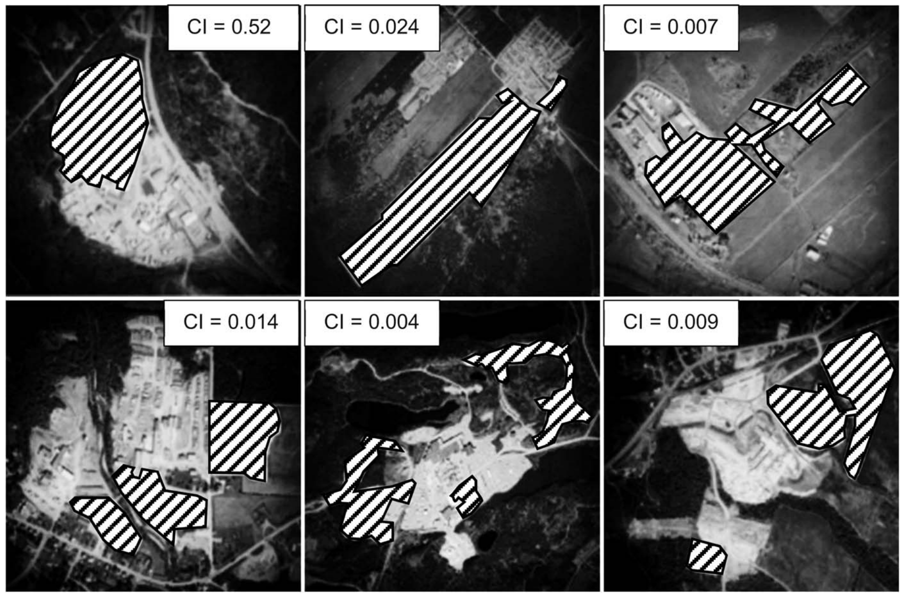

Figure 3.—Example of log yard shape diversity. CI = compactness index. Source: Google Earth Pro 2016.

constraints on wood transportation, requiring a significant extension of the storage area for inventory surge at the mill yard. Inventory strategies and wood supply requirements may explain the need for a larger storage area.

Inventory management

To respond adequately to production demand in terms of quality (freshness) and quantity of raw material, log yards are operated according to one (18%) or several (82%) inventory management strategies. Three main inventory strategies are reported by respondents: just-in-time (JIT), first-in, first-out (FIFO), and freshness wood management (FWM). In JIT, only an adequate quantity of logs is ordered and received on an as-needed basis in the production process. FIFO retrieves raw material as a function of the receipt date. Logs delivered earlier are transformed earlier. Lastly, FWM uses logs in connection with the harvesting date to preserve freshness. Log freshness is one of the most important matters in inventory management, as dry log transformation increases energy consumption by 30 percent, decreases the quality of sawn timber, and produces lower-quality chips (Mackay 2002).

Seventy-six percent of log yard respondents applied the JIT strategy, followed by the FWM (60%) and FIFO (45%). Implementing the JIT strategy, which allows unloading trucks directly at the mill in-feed with a minimal on-site wood inventory, can reduce yard handling costs by Can\$1.9 per m^3 (Tran 2009). When possible, better in-flow management could reduce required storage space and minimize equipment movements. However, this strategy requires good forest–sawmill operation coordination to deliver adequate raw material (species, format, diameter, and quantity) at the appropriate time. Such coordination imposes a logistical burden, which may bring new costs or transfer costs upstream in the supply chain (to the forest). Also, this strategy may not be applicable year round, especially during thaw periods when transport is stopped to preserve the roads.

Wood is delivered in log-length or in tree-length formats (logs of more than 18 ft). Most surveyed log yards store cut-to-length wood. The proportion of this format varies from 10 to 100 percent of volume with a median of 96.5 percent (mean of 73%). The proportion of log yards purchasing exclusively cut-to-length wood (47%) justifies this high median.

All respondents reported sorting raw material according to at least one criterion. Figure 5 presents the sorting characteristics: sorting criteria (A) and number of sorts (B). The primary criteria are tree species (82%), length (66%), and diameter (42%). Wood provenance was used as a sorting criterion by 16 percent of respondents and wood freshness by 8 percent. The number of wood sorts ranged from 1 to 15 (mean of 5, median of 4). The number of assortments is not correlated with annual volume (Spearman's correlation, $\rho = 0.2167$, $P = 0.1914$), but yards with more assortments require more space (Spearman's correlation, $\rho = 0.3609$, $P = 0.0260$). Almost half of surveyed yards (47%) reported class-based storage location. The

Table 2.—Type and proportion of surface material used in the surveyed yards (n = 38).

Type of surface material	Proportion of surface material (%): 0	1–20	20–40	40–60	60–80	80–100
	Share of log yards (%)					
Asphalt	60.5	24	13	2.5	0	0
Gravel	18.5	18.5	18.5	8	10.5	26
Beaten earth	37	5.5	5.5	5.5	21	26

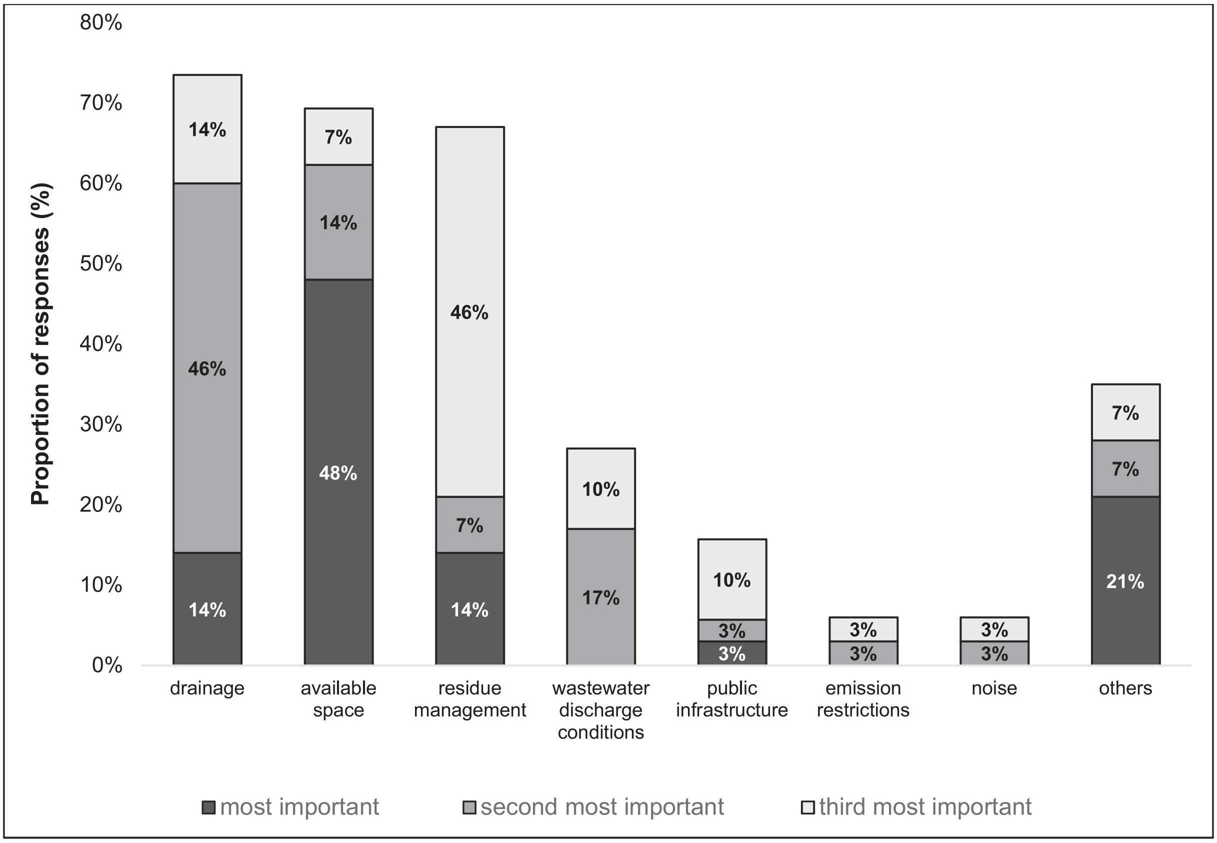

Figure 4.—The most important constraints on log yard design according to log yard managers (n = 29). The category "other constraints" encompasses weather conditions, inventory turnover, variation of reception, and space conflict with lumber.

other respondents applied sort allocation according to available space with some considerations of efficiently allocating various log formats (e.g., cut-to-length closer to the mill deck). Allocating raw material according to available space limits the access to recovery of older logs, leading to a decrease in wood value. Type and number of wood sorts will influence the type of handling equipment in the yard.

Handling equipment

Equipment fleet in the surveyed log yards consisted of mobile loaders (67%), front-end loaders (13%), stationary loaders (7%), trucks (6%), mobile slashers (6%), and mobile debarkers (1%). The log yards used one to six main handling machines that were mobile loaders or front-end loaders with a utilization rate above 60 percent. More than half of surveyed yards (55.3%) used two main machines (Table 3).

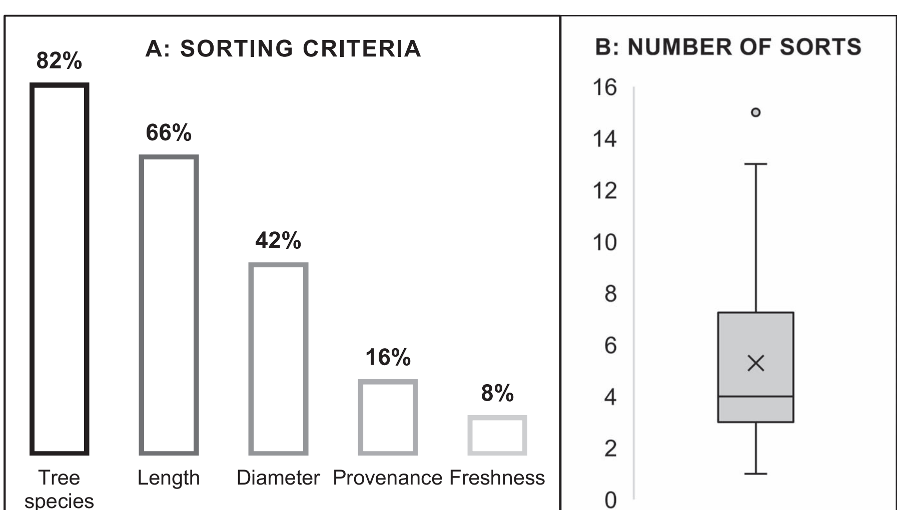

Figure 5.—Sorting criteria (A) and number of sorts (B) for the 38 surveyed yards.

Table 3.—Number of handling machines employed by yards ($n = 38$).

Machine category	No. of handling machines 0	1	2	3	4	>4
Main (% of log yards)	—	7.9	55.3	18.4	13.1	5.3
Spare (% of log yards)	42.1	44.7	7.9	5.3	—	—

Most log yards (57.9%) relied on spare machines. These were used in case of downtime of the main machines or for increased capacity during peak hours.

Figure 6 shows the age of handling machines in the survey. The average age of main and reserve machines is 17 and 18 years, respectively. The age of the main machines varies from 3 to 44 years; age of reserve machines, 10 to 30 years. More than a quarter of the main machines are older than the mean age of the reserve machines. Some managers believed that their old machines adapted well to their yard.

Seasonality impact

One of the major factors influencing log yard design is seasonality. This factor was investigated through raw material inventory levels and utilization of yard capacity (area, equipment, labor) during the year.

There are significant differences between the quantities of wood stored in the high and low seasons (Wilcoxon signed-rank, $Z = 5.3776$, $P < 0.001$, $n = 38$). In general, the maximum volume is reached in March (mean of 87,000 m^3), whereas the minimum is in June (mean of 35,000 m^3). These variations are largely induced by transport interruption during the thaw period. However, as shown in Figures 7A and 7B, a large range of variation can be observed among the yards. The inventory variation (coefficient of variation) ranges from 18 up to 76 percent, with an average of 38.5 percent (Fig. 7A). The amplitude of inventory level between high and low seasons varies from 7,000 to 280,000 m^3 (mean of 86,420 m^3), and exceeds 100,000 m^3 in 34 percent of log yards (Fig. 7B). Since wood reception variations are difficult to control, the log yard must be designed to handle and store different inventory levels.

In the high stocking season, a larger share of the available yard area is used to accumulate logs in order to continue mill production during the thaw period. Storage zones with a soft coating are emptied first. The zones located far from the mill deck are used only once a year, while the inventory turnover rate of closer zones can reach six times per year.

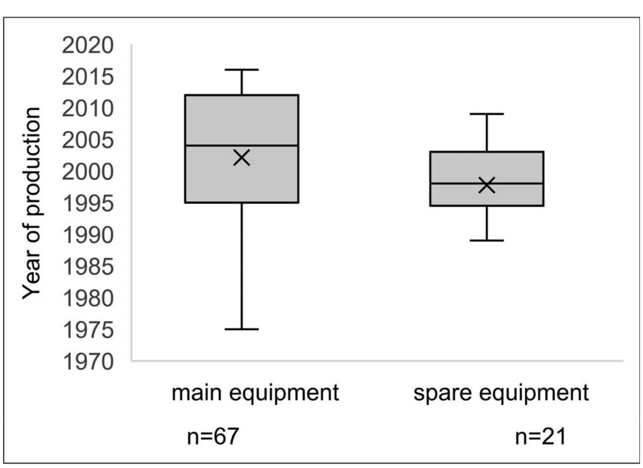

Figure 6.—Year of production of handling equipment used in surveyed yards.

The number of pieces of handling equipment differs between high and low seasons. As it was noted during on-site visits, 60 percent of visited yards use one additional machine in the high period (3 mo per year) to support the unloading capacity of the increased truck arrival frequency.

The seasonality of wood supply also affects the number of yard employees. In the high season, the median number of employees is 33 percent higher than in the low period (Wilcoxon signed-rank, $Z = 2.0056$, $P = 0.0485$, $n = 38$). These variations can reach up to 50 percent for the number of equipment operators (who represent 55% of total yard employees). Other employees include scalers (19%), mechanics (15%), yard supervisors (10%), and welders (1%). Log yards frequently function on two shifts in both high and low seasons (52.5% and 50%, respectively). Twenty-one percent of surveyed yards are operated 24 hours per day during the whole year. Furthermore, 13 percent of additional yards are operated 24 hours per day only in the high season. One sawmill reported not operating during the low season.

Seasonal variations in log yard activities make design and inventory management more complex, for the yard's capacity and wood flow must be balanced. The best solution for that issue could be to adjust the wood supply strategy and apply JIT policy as long as possible. Otherwise, log yards should be flexibly designed to manage under- or overcapacity during the year (i.e., rental of handling equipment, flexible space allocation shared with finished products) in order to maintain high performance within the year.

Log yard performance

Performance evaluation.—Managers were asked to indicate the criteria they use to evaluate and monitor their yard performance. Sixty-seven percent of yard managers ($n = 36$) considered their log yard "efficient." Only 26 percent of surveyed log yard designs have been systematically evaluated and improved over the last 15 years. Surprisingly, 8 percent of respondents declared not using any performance criteria for the log yard. Eighteen percent of respondents used only one performance indicator, while the remaining 74 percent used up to six performance indicators. Table 4 reports the performance indicators used in the surveyed yards. The main performance criteria are operational costs (71%) and average truck cycle time (63%). Although 60 percent of respondents declared applying the FWM inventory management strategy, only 46 percent reported using wood freshness as a performance indicator.

Truck cycle time data is easy to obtain and is therefore commonly used by log yard managers in performance measurement. In surveyed yards, the average truck cycle time differs depending on the type of truck–trailer

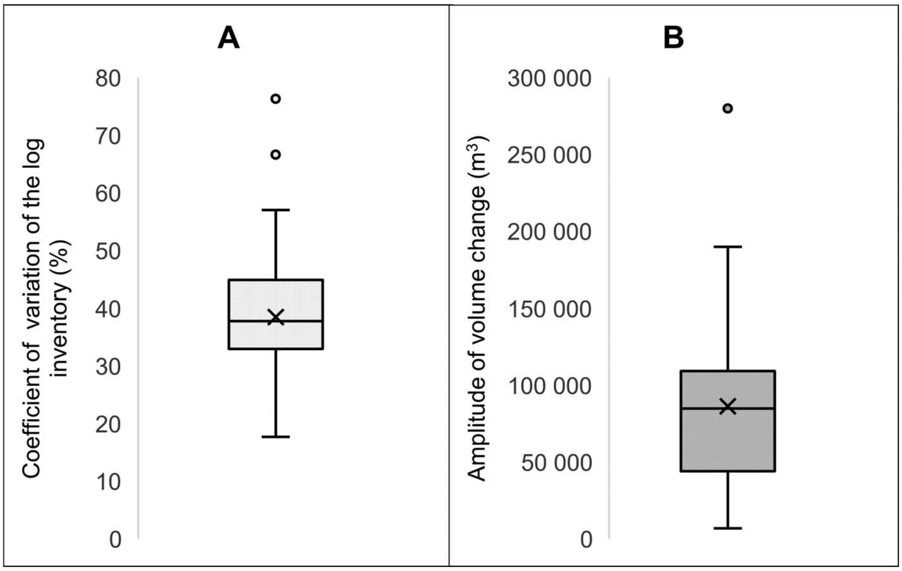

Figure 7.—Coefficient of variation of log inventory (A) and yearly volume fluctuation (B) for the surveyed yards (n = 38).

configuration and the season (Table 5). As could be expected, cycle time slightly increased in the high season, partly offset by an increase in handling capacity and employees. According to Deckard et al. (2003), the most important factors affecting truck cycle time are log yard layout and maintenance (lack of inventory space, poor road conditions), equipment systems, human resources, and government regulations. Truck cycle time partly reflects the performance of yard design and operational rules, as favorable cycle time could be the result of inadequate wood freshness management, low storage density (forming lower piles), or large number of handling machines (increase in yard operational costs), to name but a few factors.

Operational costs of surveyed log yards ranged from Can$0.80 to Can$16.50 per m^3 ($n = 26$), with a median of Can$2.40 per m^3 (mean of Can$3.45 per m^3). The survey highlighted the lack of clear agreement on operational cost components, more specifically cleaning and maintenance costs, municipal taxes, rental costs, staff costs, and raw material deterioration. These costs represented a nonnegligible part of the wood supply costs. According to Del Degan and Larouche (2016), the average transformation cost for the fir–spruce–pine–larch sawmills in Quebec is Can$37.52 per m^3. Therefore, the operational costs of our sample represent almost 6 percent of total transformation costs.

Managerial perception of key performance factors.—The log yard managers were also asked to indicate the most important factors to obtain an efficient yard design. Eighty-seven elements were provided by respondents, classified into 11 factors (Table 6). Twenty-four percent of respondents saw solid surface as a means for improving performance. The managers of surveyed yards with asphalt surface confirmed a significant improvement in wheeled equipment work (higher speed and facilitated maintenance) and residue management (smaller costs and facilitated operation). The hard surface was strongly recommended by Sinclair and Welburn (1984), especially for the yards processing more than 140,000 m^3 annually. However, the beaten earth surface negatively affected log yard performance by decreasing or precluding the access to some parts of storage area during the thaw period. Consequently, 34 percent of yard managers who planned to invest in their log yard within the next 5 years declared to have prioritized surface material and drainage ($n = 44$).

Minimizing in-yard transport distance was identified by survey respondents as another key aspect to design an efficient log yard (21% of responses), which is also highlighted in Tran (2009). There are two associated issues. The first involves understanding the importance of the log yard's compact shape, limited often by its localization

Table 4.—Log yard performance indicators used by respondents (n = 35).

Indicator	Frequency (%)
Operational costs	71
Truck cycle time	63
Wood freshness	46
Volume per day	34
Broken logs (%)	20
Conformity of the mix at deck	11.5

Table 5.—Average truck cycle time[a] in the log yard for the high and low seasons based on 46 trucks.

Truck–trailer configuration	High season (min)	Low season (min)
Semi-trailer		
Median	33	30
Mean	35	28
Range	20–60	10–45
B-train		
Median	30	29
Mean	37	29
Range	21–60	20–45
Oversize		
Median	42	38
Mean	42	38
Range	30–60	20–60

[a] Truck cycle time corresponds to the time elapsed between weighting time on arrival and weighting time when leaving the log yard.

Table 6.—Factors contributing to efficient design in manager's perception (n = 87).

Factor	Frequency (%)
Solid surface	24
Layout minimizing distances	21
Adequate space	12
Inventory freshness management	10
Delivery forecast	8
Optimization of storage space	7
Well-trained staff	6
Adapted equipment	6
Security in the yard	3
Yard's environmental impact	2
Residue management	1

(neighborhood, environmental limits, and sloping area). The second involves optimizing yard layout for a given shape. It concerns adequate sort allocation using class-based storage policy (more important sorts nearby the mill deck) and stacking the piles as high as equipment capacity permits.

Other important factors include adequate space (12% of responses) and inventory freshness management (10% of responses). Wood inventory management was identified as the key factor during on-site visits. Stocking sorted logs by species and diameter classes has been identified as crucial for feeding the mill with the appropriate log mix. Controlling the log mix at the deck can increase sawmill productivity from 3.5 to 4.5 percent of lumber volume per shift according to implemented control method (Goulet 2007). Log yard managers are keen to improve their inventory management in wood freshness and traceability control.

Equally important design factors identified by the log yard managers are well-adapted handling equipment (6%) and well-trained employees (6%). Inadequately trained operators decline the operational performance, spoil handling equipment, and decrease the log transformation value. Hence, 18 percent of planned investments in log yards involved employee training ($n = 44$).

The survey results highlight the need for a design method that accounts for sites and regional wood supply conditions. The log yards in our sample could gain in competitiveness by improving their design practices, as discussed in Trzcianowska et al. (2019). From survey answers and interviews with log yard staff, we realized that log yard managers are keen to obtain structured log yard design guidelines that could improve their performance. That statement is consistent with the warehouse research recommendations proposed in Davarzani and Norrman (2015). They highlighted the practitioner's interest in warehouse business tools that design a warehouse and measure its performance. We assume that the need for structured log yard design methods exceeds the Quebec regional sample. Given the important impact that log yards may have on the wood supply chain efficiency, it is crucial to further investigate yard performance.

Conclusions

The gaps found in the literature led us to investigate the current practices of log yard design in a practical environment. Based on a sample of large softwood sawmills in eastern Canada, the results highlighted the heterogeneity of operational conditions and the lack of explicit log yard design rules or best industrial practices. Only 26 percent of the surveyed log yard designs have been systematically evaluated and improved over the last 15 years. Most current log yard designs have simply evolved over time as an ''intelligent improvisation'' without specific design considerations or performance evaluation. This simple evolution without structured performance monitoring seems quite surprising, in comparison with continuous improvement in warehousing efficiency in other industrial fields.

All investigated log yards are influenced by seasonality of wood delivery. Their fluctuation levels range from 18 to 76 percent. These fluctuations have an impact on utilization of yard resources and performance measurement throughout the year. Designing a log yard based on high/low period volume estimation requires some flexibility in managing yard capacity. High seasonal surges significantly increase storage density, imposing a challenge for design adaptation in accordance with temporary requirements. Consequently, the emphasis should be placed on a supply strategy that applies JIT during the longest possible period. Otherwise, the log yard should be designed to manage under- or overcapacity throughout the year (i.e., rental of handling equipment, flexible space allocation shared with finished products).

Moreover, three factors are identified as critical performance inhibitors: irregular log yard shape, excessively large area, and limited use of hard surface. Irregular log yard shape and large area increase equipment travel distance. As presented by Trzcianowska et al. (2019), the number of main log yard resources (handling equipment and labor) is associated with the log yard shape. Whenever possible, land should be acquired and prepared to adopt an optimal yard shape. Otherwise, the emphasis should be focused on layout configuration (location of circulation aisles and product allocation) as is the case in warehouse design optimization (e.g., Tremblay et al. 2012, Roodbergen et al. 2015). Forty-eight percent of respondents mentioned the need for additional space, though the average yard area is large enough. This result points toward the need for better space utilization by improving storage density and managing wood flow to avoid inventory variation as much as possible. The third inhibitor, the inadequate surface material, impedes drainage and residue management.

The survey results emphasized an incoherence in managers' responses regarding the most important constraints. The need for extra space in large yards may be due to inaccurate control over inventory policies. Matters surrounding drainage and residue management require a solid surface material. Unfortunately, only 15.5 percent of log yards have more than 20 percent of surface asphalted; only 26 percent of log yard managers plan to invest in solid surface in the next 5 years. Above all, the survey highlighted the lack of rigor in estimating log yard cost and benefits of design improvement (i.e., asphalted surface). A structured investigation of log yard design is required to improve the facility's efficiency and the wood supply interaction.

This first project is part of a broader initiative to lead to the development of a systematic method of log yard design. Current methods are static and do not take into account the seasonal adaptation needs of design and operations. Work in progress aims at including seasonality considerations in managers' decision making in order to increase performance.

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Literature Cited

Alam, M. B., C. Shahi, and R. Pulkki. 2014. Economic impact of enhanced forest inventory information and merchandizing yards in the forest product industry supply chain. *Socio-Econ. Plann. Sci.* 48(3):189–197.

Baker, P. 2008. The design and operation of distribution centres within agile supply chains. *Int. J. Prod. Econ.* 111(1):27–41.

Baker, P. and M. Canessa. 2009. Warehouse design: A structured approach. *Eur. J. Oper. Res.* 193(2):425–436.

Beaudoin, D., L. LeBel, and M.A. Soussi. 2012. Discrete event simulation to improve log yard operations. *INFOR: Inf. Syst. Oper. Res.* 50(4):175–185.

Christopher, M. and D. Towill. 2001. An integrated model for the design of agile supply chains. *Int. J. Phys. Distrib. Logist. Manag.* 31(4):235–246.

Cormier, G. and E. A. Gunn. 1992. A review of warehouse models. *Eur. J. Oper. Res.* 58(1):3–13.

Da Cunha Reis, A., C. G. de Souza, N. N. Da Costa, G. H. C. Stender, P. S. Vieira, and N. D. Pizzolato. 2017. Warehouse design: A systematic literature review. *Braz. J. Oper. Prod. Manag.* 14(4):542–555.

D'Amours, S., M. Ouhimmou, J. F. Audy, and Y. Feng. 2016. Forest Value Chain Optimization and Sustainability. CRC Press, Boca Raton, Florida.

Davarzani, H. and A. Norrman. 2015. Toward a relevant agenda for warehousing research: Literature review and practitioners' input. *Logist. Res.* 8(1). DOI:10.1007/s12159-014-0120-1

Deckard, D. L., R. A. Newbold, and C. G. Vidrine. 2003. Benchmark roundwood delivery cycle-times and potential efficiency gains in the southern United States. *Forest Prod. J.* 53(7):61–69.

De Ketele, J. M. and X. Roegiers. 2009. Méthodologie du Recueil d'Informations: Fondements des Méthodes d'Observation, de Questionnaires, d'Interviews et d'Études de Documents [Methodology Of Information Collection: Foundations of Observation Methods, Questionnaires, Interviews and Document Studies]. 5th ed. De Boek Supérieur, Louvain-la-Neuve, Belgium. (In French.)

Del Degan, B. and A. Larouche. 2016. Étude comparative des coûts d'approvisionnement et de transformation Québec/Ontario [Comparative study of procurement and processing costs Quebec/Ontario]. Groupe DDM, Quebec, Canada. (In French.)

Dotoli, M., N. Epicoco, M. Falagario, N. Costantino, and B. Turchiano. 2015. An integrated approach for warehouse analysis and optimization: A case study. *Comput. Ind.* 70(1):56–69.

Dramm, J. R., R. Govett, T. Bilek, and G. L. Jackson. 2004. Log sort yard economics, planning, and feasibility. General Technical Report FPL-GTR-146. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin.

Dramm, J. R., G. L Jackson, and J. Wong. 2002. Review of log sort yards. General Technical Report FPL-GTR-146. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin.

Favreau, J. 2002. Opti-Stock: Un modèle pour déterminer l'impact du stockage des bois sur les coûts [Opti-Stock: A model to determine the impact of wood storage on the costs]. *In:* Seminar on Wood Storage: Problems and Solutions, March 26, 2002, Pointe-Claire, Quebec, Canada; Forest Engineering Research Institute of Canada (FERIC), Pointe-Claire, Quebec. pp. 1–11. (In French.)

Goh, M., O. Jihong, and T. Chung-Piaw. 2001. Warehouse sizing to minimize inventory and storage costs. *Naval Res. Logist.* 48(4):299–312.

Goulet, P. 2007. Utilisation de la simulation du flux d'une scierie pour déterminer les gains en productivité associés au triage des tiges par dimensions [Using the samill flow simulation to determine the productivity gains associated with sorting stems by dimensions]. Master's thesis. Université Laval, Quebec, Canada. (In French.)

Gu, J., M. Goetschalckx, and L. F. McGinnis. 2007. Research on warehouse operation: A comprehensive review. *Eur. J. Oper. Res.* 177(1):1–21.

Gu, J., M. Goetschalckx, and L. F. McGinnis. 2010. Research on warehouse design and performance evaluation: A comprehensive review. *Eur. J. Oper. Res.* 203(3):539–549.

Hampton, C. M. 1981. Dry Land Log Handling and Sorting: Planning, Construction, and Operation of Log Yards. Miller Freeman Publications, San Francisco.

Huka, M. A. and M. Gronalt. 2018. Log yard logistics. *Silva Fennica* 52(4). DOI:10.14214/sf.7760

Hultqvist, D. and L. Olsson. 2004. Demand based tactical planning of the roundwood supply chain with respect to stochastic disturbances. FSCN, Mitthögskolan, Sweden. 58 pp.

Kons, K., D. Bergström, U. Eriksson, D. Athanassiadis, and T. Nordfjell. 2014. Characteristics of Swedish forest biomass terminals for energy. *Int. J. Forest Eng.* 25(3):238–246.

Kostrzewski, M. 2014. In search of unified warehouse designing method. *Res. Logist. Prod.* 4(3):257–266.

LeBel, L. and J. S. Carruth. 1997. Simulation of woodyard inventory variations using a stochastic model. *Forest Prod. J.* 47(3):52–57.

Lee, M. K. and E. A. Elsayed. 2005. Optimization of warehouse storage capacity under a dedicated storage policy. *Int. J. Prod. Res.* 43(9):1785–1805.

Lehoux, N., S. D'Amours, J. Beaulieu, P. Marier, and D. Ouellet. 2012. Le réseau de création de valeur de la fibre de bois canadienne [The value creation network of Canadian wood fiber]. Scientific Report CIRRELT-2012-33. Laurentian Forestry Centre, Quebec, Canada. (In French.)

Mackay, G. 2002. Stockage du bois: problèmes et solutions [Wood storage: Issues and solutions]. *In:* Seminar on Wood Storage: Problems and Solutions, March 26, 2002, Pointe-Claire, Quebec, Canada; Forest Engineering Research Institute of Canada (FERIC), Pointe-Claire, Quebec. (In French.)

Mendoza, G. A., R. J. Meimban, P. A. Araman, and W. G. Luppold. 1991. Combined log inventory and process simulation models for the planning and control of sawmill operations. Presented at the 23rd CIRP International Seminar on Manufacturing Systems, June 6–7, Nancy, France, 1991.

Moore, J. and D. Cown. 2015. Wood quality variability—What is it, what are the consequences and what we can do about it. *N. Z. J. Forestry*. 59:3–9.

Myers, J. and E. W. Richards. 2003. Supporting wood supply chain decisions with simulation for a mill in northwestern BC. *INFOR: Inf. Syst. Oper. Res.* 41(3):213–234.

Rathke, J., M. A. Huka, and M. Gronalt. 2013. The box assignment problem in log yards. *Silva Fennica* 47(3):1–13.

Roodbergen, K. J., I. F.A. Vis, and G. D. Taylor. 2015. Simultaneous determination of warehouse layout and control policies. *Int. J. Prod. Res.* 53(11):3306–3326.

Rouwenhorst, B., B. Reuter, V. Stockrahm, G. J. van Houtum, R. J. Mantel, and W. H. M. Zijm. 2000. Warehouse design and control: Framework and literature review. *Eur. J. Oper. Res.* 122(3):515–533.

Sedney, D. G. 1992. Simulation of a log merchandising and sorting yard. Master's thesis. University of Idaho, Moscow.

Sinclair, A. W. J. and G. V. Wellburn. 1984. A Handbook for Designing, Building and Operating a Log Sortyard. Forest Engineering Research Institute of Canada, Vancouver.

Strack, G. and Y. Pochet. 2010. An integrated model for warehouse and inventory planning. *Eur. J. Oper. Res.* 204(1):35–50.

Thomas, J. J. and K. F. Wallis. 1971. Seasonal variation in regression analysis. *J. R. Stat. Soc Series A (General)* 134(1):57.

Tompkins, J. A., J. A. White, Y. A. Bozer, and J. M. A. Tanchoco. 2010. Facilities Planning. 4th ed. John Wiley & Sons, New York.

Tran, E. 2009. Efficacité d'utilisation des chargeuses dans les parcs à bois: Quatre études de cas [Efficiency of loaders's utilization in the wood yards: Four case studies]. Advantage Report 10(9). Forest Engineering Research Institute of Canada (FERIC), Pointe-Claire, Quebec. 8 pp. (In French.)

Tremblay, E., F. F. Boctor, and J. Renaud. 2012. Impacts de la configuration de l'entrepôt et de la localisation des produits sur l'efficacité des parcours de collecte: Un cas réel [Impacts of warehouse configuration and product localization on the efficiency of collection pathways: A real case]. Scientific Report CIRRELT-2012-54. Laurentian Forestry Centre, Quebec, Canada. (In French.)

Trzcianowska, M., L. LeBel, and D. Beaudoin. 2019. Performance analysis of log yards using data envelopment analysis. *Int. J. Forest Eng*. 30(2):144–154.

Vachon-Robichaud, S., D. Beaudoin, and L. LeBel. 2014. Log yard design using discrete-event simulation: First step towards a formalized approach. Presented at MOSIM 2014, 10ième Conférence Francophone de Modélisation, Optimisation et Simulation, November 5–7, 2014, Nancy, France.

Van den Berg, J. P. 2007. Integral Warehouse Management: The Next Generation in Transparency, Collaboration and Warehouse Management Systems. Management Outlook Publishing, Utrecht, the Netherlands.

Williston, E. M. 1976. Lumber Manufacturing. The Design and Operation of Sawmills and Planer Mills. Miller Freeman Publications, San Francisco.

Yammarino, F. J., S. J. Skinner, and T. L. Childers. 1991. Understanding mail survey response behavior: A meta-analysis. *Publ. Opin. Q*. 55(4):613–639.

Yu, J. and H. Cooper. 1983. A quantitative review of research design effects on response rates to questionnaires. *J. Mark. Res*. 20(1):36–44.

Yujie, Z. and W. Fang. 2009. Study on the general plane of log yards based on systematic layout planning. *In:* 2009 International Conference on Information Management, Innovation Management and Industrial Engineering, December 26–27, 2009, Xi'an, China, Vol. 4; Institute of Electrical and Electronics Engineers (IEEE), New York. pp. 92–95.