INTEGRATED MILL/RESOURCE CAPACITY PLANNING IN THE CANADIAN FOREST INDUSTRY
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ABSTRACT
To a great extent, the design of large forest products facilities has been based on the assumptions of stable future wood costs and species mix. Mill design and wood supply are dealt with as separate, although connected, calculations. This is essentially an agricultural model in which supply is available at a relatively constant rate and is spread uniformly over the supply area. This paper questions this assumption, contrasting it to the situation in the mineral industries, in which there is an intimate connection between mill capacity and production rate and the definition of the resource, with complex cost structures that depend on the planned schedule of resource exploitation.

INTRODUCTION
At the heart of forestry in Canada is the concept of sustainability embedded in the Canadian Council of Forest Ministers (CCFM) statement on Criteria and Indicators of Sustainable Forest Management [1]. Membership in the Forest Products Association of Canada (FPAC) (see http://www.fpac.ca/) is conditional upon third-party certification of sustainable forest management under at least one of Canada Standards Association, Forest Stewardship Council, or Sustainable Forestry Initiative (see http://certification-canada.org/). To a certain extent, this approach reflects a viewpoint that the forest resource is an entity to be managed in its own right for many objectives that include economic benefits.

This approach can be contrasted with the definition of resource in the mineral industry. In Canada, most securities commissions require that companies reporting on mineral reserves must do so within the context of NI-43-101 [2], which in turn references the Canadian Institute of Mining, Metallurgy, and Petroleum Standards [3]. These standards imply that the definition of a resource goes hand in hand with an economic plan to exploit it.

Some parts of the Canadian forest industry may have more in common with a mining situation than with the conventional thought process assuming an infinitely renewable resource. Two examples are the old-growth forests of the west coast and the slow-growing boreal forests of northern Canada, with rotation periods of more than 100 years. However, even within Canadian forests where the concept of a somewhat constant supply makes sense, there are issues that might cause reconsideration of what defines a forest resource for economic purposes. These issues become pressing when industry capacity issues are considered.

Like mining and oil processing, forest processing is highly capital-dependent. Modern facilities for lumber, pulp, paper, and various other forms of forest biomass processing exhibit substantial economies of scale in both capital and labour. In the mineral industry, defining the resource requires a definition of processing costs, which in turn requires a definition of processing scale. To put in place the new capacity required to carry out the forest-sector transformation envisaged in FPAC’s biopaths documents [4] and other federal documents [5], it must first be determined how this capacity is related to the forest resource.

This paper is a discussion paper, with the aim of questioning current approaches. The mining industry approach to resource definition and capacity planning is briefly reviewed, noting the view that the definition of the resource depends on how it will be used. Next, the usual approach to defining the forest resource is examined. In this case, the forest resource is defined independently of its use. This has significant implications for the design of the capital structure in an industry where both capital and transportation exhibit economies of scale. Three simple mathematical models are introduced to shed some light on the discussion. The forest harvesting and mine planning model are similar in their level of complexity. However the mine-planning model explicitly contains the costs of resource acquisition, and the mining rates depend on capital cost decisions. A simple capacity planning model provides insight into the more complex capacity issues in the forest industry, where economies of scale in capital blend...
with the complexity of transportation of multiple products in an integrated system. The question raised here is how economically sustainable can an industry be when resource definitions are developed without careful attention to the profitability of the industry using the resource.

MINING AND FORESTRY: SIMILARITIES AND DIFFERENCES

There are many similarities between the mining and forest products industries. Both have major effects on rural communities, where the economic activity of these industries affects both direct employment and, importantly, indirect employment (food services, transportation, accommodations, etc.). The ability to provide rural infrastructure is often dependent on one or both of these industries. Both are under the control and influence of provincial governments. Mineral rights in Canada belong to the Crown (the Provincial governments), even on land otherwise privately owned. In most provinces, the Crown owns the majority of forest land, although every province has significant amounts of private land. Government is often involved in providing incentives for capital investment in both types of industries.

Both industries are heavily dependent on capital investment, not only for processing facilities, but also for material acquisition and transportation equipment. Both are heavily automated from material acquisition through to processing. Most labour involves equipment operation and maintenance activities. For both industries, economies of scale in labour and capital equipment are important.

Both industries involve acquiring raw material. The cost of acquiring this material and transporting it to processing facilities can be a significant fraction of production costs. Both imply significant amounts of energy utilization. Both benefit from value-added activities, and their locations in relation to value-added facilities and markets are important.

There are also apparent differences. It is impossible to think of forestry without thinking about multiple products and processing facilities. Sawlogs, pulpwood, and possibly biomass material of a variety of species, produced from harvesting or thinning, need to go to sawmills, pulp mills, and energy facilities for final use, although the use of intermediate facilities may improve transportation logistics. At the sawmill, breakdown of a log into hundreds of products is normal. Typically, more than 50% of sawmill input emerges as chips, sawdust, shavings, and bark for input to pulp mills and energy facilities. By contrast, most mining involves processing ore through a single mill facility. Although the ore may involve multiple (two to five) recoverable minerals, typically the milling process produces a single concentrate, which then goes to a remote smelter for recovery of individual metals. In some places (for example, Sudbury, Ontario), there is a mining infrastructure involving multiple mines, multiple mills, and one or more smelting facilities.

One claim for distinction is that mining is exhaustive, while forestry is sustainable. Because trees grow, forest management policies can maintain and increase the amount and quality of the growing stock over time, both in individual locations and regionally. Mining involves removing material that will never be replenished. However, there are forestry situations that will never be repeated. Old-growth forests, particularly on the west coast, will not be replenished in the same form. The boreal forest is very slow-growing, with rotation periods approaching 100 years, an economic period that is effectively infinite. Sustainability is not about constancy; it is an economic concept, involving current benefits to society without impairing the prospects of future generations. It does require a commitment to maintaining biodiversity, soil, air, water, and ecosystem health. In both industries, this involves restoring the land to an acceptable condition following use. Applying the CCFM’s six criteria [1] for SFM to mining, it is unclear that mining is less sustainable than forestry.

One common issue is highgrading, a process in which the resource is exploited so as to impair the subsequent ability to use the resource. In forestry, this would include harvesting policies which remove the most valuable trees from a stand, making it uneconomical to access the remainder. Another example is road access policies that target valuable, easily accessible stands in the short term, leaving behind poor-quality stands. These stands can deteriorate in quality over time, making them even less likely to be accessed in the future. A similar issue occurs in mining. A mine plan proceeds as a series of pushbacks, where pushback PB(t) consists of all the blocks mined in period t. The optimal pushback PB(t) in period t for the long-term problem with a time horizon T is typically not the set of blocks that would be mined if the mine planning problem were to end in period t. Instead, much more complex mine development algorithms are necessary to avoid highgrading the deposit (see examples in [6]). In both mining and forestry, current decisions have future consequences. A decision to harvest a stand now determines when that stand will regenerate and be available for a subsequent harvest. A (costly) thinning done now will lead to better quality and reduced costs later when the final harvest occurs.

The quality of material acquired and the cost of acquisition of that material are not constant. This is obvious in the case of mining for an ore body that varies in quality and where mining extends deeper over time. However, in forestry, even if an annual allowable cut is respected, the age and quality of the trees harvested and the location of harvesting will inevitably vary over time. Without some care, this can create another type of highgrading in which the closest material is harvested in the early years and material acquisition costs increase over time.

ECONOMIES AND DISECONOMIES OF SCALE: WHY CAPACITY MATTERS

Like most process industries, pulp, lumber,
and other biomass production facilities are subject to economies of scale. Although there are no precise ways to estimate how capital costs vary with capacity, a working rule has been the “six-tenths rule,” which states that the costs of doubled capacity are $2^{0.6}$ times base capacity [7]. A commonly used cost estimating function is

$$C(X) = K X^a$$

where $X$ is some measure of capacity and $K$ and $a$ are constants, with $a$ between 0.6 and 0.7. Lieberman [8] points out that this relation may vary when new capacity requires technological change and the accompanying engineering. Whatever functional form is used, economies of scale imply that the average cost per unit declines with capacity. Economies of scale do not affect capital only. Doubling the capacity of a plant seldom means doubling the number of workers. Evidence of the importance of scale can be seen in the growth of plant size in the chemical industry.

In the pulp and paper industry, plant capacities are rising. UPM Kymmene’s eucalyptus pulp mill in Fray Bentos, Uruguay has a production capacity of 1.1 million air-dried tonnes per year. The largest Kraft mill in the world is reported to be the Asia Pacific Resources International Limited (APRIL) Riaupulp (Indonesia) mill, at two million tonnes. In contrast, most Canadian mills are in the 300,000-tonne range. Towers and Francis [9] point out that if more modern technology were used, considerable savings in energy and greenhouse emissions would be possible. Modern mills would be in the 500,000- to 600,000-tonne range.

Compared to other industries, the scale of even modern pulp mills is small. The Imperial Oil Refinery in Dartmouth, NS, considered very small at 82,000 barrels per day, is equivalent to 4.3 million tonnes per year of material with an input value of $2.4$ billion (at $80 per barrel). A modern refinery, such as the 300,000 barrel per day Irving refinery in St. John, NB, is approximately four times larger. In contrast, an average-sized 300,000-tonne Kraft pulp mill has an output value of product of $270$ million (at $900 per tonne). A mine such as Teck’s Highland Valley copper mine processes approximately 42 million tonnes per year (average grade 0.27% copper, 86% recovery), producing 98,500 tonnes of copper valued at more than $689 million (at $7000 per tonne). The input to the 300,000-tonne Kraft pulp mill would be approximately 1.7 million tonnes of green wood. The mine handles 20 times the amount of material, and the value of product is more than twice as high.

Economies of scale affect not just Kraft mills, but also newsprint, solid lumber, OSB, and any form of biorefinery that is likely to appear. Economies of scale in labour are particularly important for sawmills. Why then are forest products capacities so small? One reason is the cost of material acquisition. Acquiring more forest products typically implies longer transportation distances. For example, assuming a circular area to acquire the resource (the best case) and a constant production per unit area, the transportation cost per tonne rises more than linearly with annual demand. Figure 2 illustrates this using two different calculation methods. Assume an average land capability of 4 m$^3$/ha per year with uniform land density, adjusted so that a 200-km radius would produce about 2 million m$^3$ per year. Method 1 assumes 50 m$^3$ per truckload, speeds of 70 and 90 km/h (loaded and unloaded), pickup and unloading time of 1 hour per load, fuel consumption of 66 and 251

![Fig. 1](image1.png) - Annualized capital costs per tonne as a function of capacity.

![Fig. 2](image2.png) - Increasing transportation costs with scale.
1/100km (loaded and unloaded) and cost per hour of truck and driver of $40/h. Method 2 uses a much simpler formula of $(6.50 + 0.70 \text{ per km})$ per tonne, giving a cost for a 100-km trip of $13.50.

It is worth emphasizing that that production is assumed to be uniform at a sustainable rate over the circular area every year. A progressive clear-cut, with the closest areas completely harvested each year, would give different results, with transportation costs initially lower but rising year by year. A progressive clear-cut, with the closest areas completely harvested each year, would give different results, with transportation costs initially lower but rising year by year. A progressive clear-cut, with the closest areas completely harvested each year, would give different results, with transportation costs initially lower but rising year by year.

Given that scale reduces capital costs and increases transportation costs in the forest industry, how then should scale and increases transportation costs in the forest industry, how then should scale and increases transportation costs in the forest industry, how then should scale and increases transportation costs in the forest industry, how then should scale and increases transportation costs in the forest industry, how then should scale and increases transportation costs in the forest industry.

**MINING INDUSTRY RESOURCE DEFINITION AND CAPACITY PLANNING**

Mining attempts to exploit a three-dimensional ore body. When modelling the ore body as a set of blocks, the logic of the mining method implies that, to remove a given block, a certain set of blocks must be removed previously. Open-pit mines are the easiest to visualize; the blocks immediately above the block of interest must be removed first. (In 2-D, to remove block A, blocks B, C, and D must be removed, as shown in Fig. 3). Newman et al. [6] gives a much more detailed discussion.

![Fig. 3 - Block removal restrictions.](image)

Each block will contain a certain amount of valuable minerals. There are two main decisions to be made at the block level: i) should the block be removed as part of the development of the mine? and ii) should the block be treated as ore or waste? Ore needs to be treated in the mill, while waste is taken to the waste dump.

To illustrate the issues, a mine design model formulation is given below. Let $O_b$ denote the amount of ore in block $b$. Let $g_b^k$ denote the ore recovery rate undermill scenario $k$, and let $v_i(g_b^kO_b)$, $m_i^k(O_b)$, $h_i^k(O_b)$, and $d_i(O_b)$ denote the value of the recovered ore, the mining costs, the handling and processing costs (ore blocks), and the disposal costs (waste blocks). The superscript $k$ used for these cost functions and for the overall horizon $T_k$ indicate that this model depends on some capacity scenario $k$, which determines mining equipment capacity and mill processing capacity. Let $Z_{bta}^k$ denote the decision that action $a$ is to be taken on block $b$ in period $t$. The possible actions are $o$ (ore) and $w$ (waste).

\[
V^k = C(Cap^k) + \frac{1}{(1+i)^t} R Cst(Z)
\]

\[
\begin{align*}
\text{Max} & \sum_{i=1}^T \sum_{b \in B} \left[ v_i(g_b^kO_b) - m_i^k(O_b) - h_i^k(O_b) \right] Z_{bta}^k + \left[ -m_i^k(O_b) - d_k^k(O_b) \right] Z_{teo}^k \\
\text{ST.} & \sum_{i=1}^T \sum_{a \in \{o,w\}} Z_{bta}^k \leq 1 \quad b \in B \\
& \sum_{a \in \{o,w\}} Z_{teo}^k \geq \sum_{t \in T} Z_{bta}^k \quad \beta \in P(b), \ b \in B, \ t = 2, T_k \\
& \sum_{b \in B} p_b^k(O_b) Z_{bta}^k \leq \text{Cap}_k^k \quad t = 1, T_k
\end{align*}
\]

Model 1 - Mine Planning.

where $C(Cap^k)$ is the initial capital cost of the facilities, the mining equipment, and the initial site preparation, and $RCst(Z)$ is the restoration cost of removing the processing facilities and reconfiguring the land to some sort of natural state following all the removals $Z$. Typically, the design process is an iterative one involving a choice of processing scenario $k$ and the solution of the pit optimization problem in response to $k$. These problems are computationally challenging and usually require special methods [6], [10]. Whether or not the problem is solved optimally, mining companies need to link their definition of their resource needs to the economics of exploitation over the mine life. Government and financial regulations, not to mention investors, require that a resource must be defined on the basis of the ability to exploit it economically. In the end, the resource consists of all those blocks for which $Z_{bta}^k = 1$. The optimization, and hence the definition of the resource, depends on decisions made about scale and processing rate. It also depends crucially on a discount rate and hence on the time value of money. Sensitivity analyses with regard to mineral prices and discount rates are standard industry practice.

**THE FORESTRY APPROACH TO RESOURCE DEFINITION AND CAPACITY PLANNING**

In Canada, resource definition tends to be thought of as separate from mill capacity planning. Typically, provincial forest...
Typically there is a “best prescription” that can be applied to a particular stand. For example, “best” might be defined as a rotation that maximizes mean annual increment or one that maximizes some economic value, such as the Faustman rotation. If \( C_{ik} \) denotes the return from applying prescription \( k \) to stratum \( i \), it is worth noting that \( C_{ik} \) has a more complex form:

\[
\sum_{t=1}^{T} \sum_{i=1}^{L} \sum_{r=1}^{R_i} \delta_{i} \gamma_{i} \alpha_{t} x_{ik} = C_{ik}.
\]

The \( C_{ikr} \) (or \( h_{ikr} \)) factors are the revenue (volume) in period \( t \) resulting from applying prescription \( k \) to stratum \( i \) in terms of log type \( l \) occurring in region \( r \). Similarly, \( \omega_{ikd} \) provides the habitat yields of type \( s \) in district \( d \) in period \( t \). If each land unit were managed individually to maximize its value, the overall result would be a highly variable total harvest. Therefore, some sort of flow constraint such as (4a), (4b), or (4c) is usually imposed. There may be additional constraints in terms of cover or habitat in certain areas (watersheds, ecosystems, etc.) (Eq. (5)). These models are used with time periods of 5–10 years and a time horizon of 100–200 years. In most Canadian provinces (see [11]), this type of model is used mainly to maximize the volume available, while not necessarily maximizing any particular economic value. Furthermore, the regions under consideration may be administrative regions or ecologically defined regions. Therefore, it is rare that the flow constraints correspond to the requirements of any particular mill or set of mills. Furthermore, they will often correspond to aggregate definitions (total softwood or hardwood) without specific species, size, or quality considerations. These constraints are often portrayed as ensuring some form of forest sustainability, but they are insufficient for this. It is often necessary to add such criteria as the minimum average stand age at the end of period \( T \). This model solution will often require harvesting low-quality or expensive-to-access stands, both early in the horizon so that they can regenerate in time for later harvesting, and late in the horizon to provide a non-declining or constant flow of wood.

The flow constraints raise a number of questions. The achieved maximum flow is usually referred to as the “annual allowable cut” (AAC). Provinces regularly report that the actual cut varies from the AAC. Quite often, for particular species, the actual cut is less than the AAC. This is not necessarily a good thing because the harvest in future years depends on regeneration after cutting in the early years. The AAC as calculated above is really an “ARC” (annual required cut). The flow constraints can significantly affect the definition of the resource. Consider a very simple example with a normally distributed initial age class structure with an average age of 60 years. (Note: A normal age class distribution is not as rare as foresters might expect. Refer to [16], page 16, for an example). Assuming a uniform land capability with maximum annual increment of \( 4 \text{ m}^3/\text{ha/year} \) (peak MAI at 55 years of age), the maximum achievable constant wood flow is \( 3.799 \text{ m}^3/\text{ha/year} \). An alternative form of regulation is area regulation, which means harvesting an equal area each year over a defined rotation. Rotations of 50, 55, and 60 years provide yields of 4.98, 4.79, and 4.61 \( \text{m}^3/\text{ha/year} \) over the first 50 years and 4.25, 4.23, and 4.22 \( \text{m}^3/\text{ha/year} \) over the first 100 years. (Note: These results are achieved using two very simple linear programming models based on the open-source GNU Linear Programming Kit software. These models are available from the author on request.)

Does long-term constant flow or non-declining yield then make sense as a way of defining resource availability? It is possible to define a forest planning model without flow constraints by specifying utilization capacity instead ([13], [17]). However this is not the usual practice in Canadian provinces, and there are issues with specifying capacity over 100 year+ time horizons.

If a resource is defined without reference to the capacity to use it, then how are capacity decisions made? Typically, they are made based on some assumed wood supply in terms of location and amount. There is a long history of capacity planning models in a variety of industries [18]. Vila, Martel, and Beaulieu [19] looked at specialized models for the forest industry. The following simplified formulation captures several aspects of the capacity-planning problem. Let \( X_{i,s,t}^{cap} \) be the addition of capacity of type \( s \) in location \( i \) in period \( t \). The capital cost is assumed to be a non-linear function \( C(X_{i,s,t}^{cap}) \), reflecting the economies of scale of capacity.

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Model 2 - Forest Planning.
Operating costs are assumed to be proportional to operating levels \( \text{OL}_{l,c,t} \). There are three types of flows that can occur. These include flows \( \text{WF}_{f,d,l,c,t} \) of wood type \( f \) from district \( d \) to capacity type \( c \) at location \( l \) in period \( t \), flows \( \text{CF}_{f,l,c,t} \) of intermediate product \( f \) from location \( l \) to capacity type \( c \), location \( l \) in period \( t \) and flows \( \text{MF}_{m,f,l,c,t} \) of market product \( f \) to market \( m \) from location \( l \) in period \( t \). The total wood flow of type \( f \) leaving a region \( d \) is limited by the resource availability \( \text{Res}_{d} \). At each facility, the operating levels \( \text{OL}_{l,c,t} \) are constrained by installed capacity \( \text{Cap}_{l,c,t} \). Each facility is assumed to operate according to some recipe. The recipe limits the proportion \( \gamma_{f,c}^{+}, \gamma_{f,c}^{-} \) of input of either forest wood inputs \( \text{WF}_{f,d,l,c,t} \) or of intermediate product inputs and provides for fixed conversion factors \( \beta_{f,c} \) on the incoming flows. The output of products is assumed to be in a fixed proportion \( \alpha_{f,c} \) to the operating levels \( \text{OL}_{l,c,t} \). The market for products is represented by a piecewise constant demand curve.

The time horizon for the capacity planning model is unlikely to be the same as that of the forest management model. Typical time scales for industrial investment are 20 years or less.

The key features of the model are economies of scale for capacity additions and trade-offs between a few large facilities and transportation costs. Three different types of transportation need to be considered: i) transportation of harvested material from the woods to the capacity facilities \( \text{WF}_{f,d,l,c,t} \), ii) transportation of intermediate products between facilities \( \text{CF}_{f,l,c,t} \), and iii) transportation of finished goods to market points \( \text{MF}_{m,f,l,c,t} \). The first type tends to favour small, distributed facilities. The second tends to favour clustering facilities together, and the last tends to favour facility locations with good access to markets. These transportation costs can be significant. In an example involving the harvest of 4.5 million m³ in Nova Scotia with already established facilities and markets, the (optimized) costs break down into i) $13.13, ii) $6.38, and iii) $3.63 per m³ in each of the three transportation categories per m³ harvested, for a total transportation cost of $23.14 per m³ or $105 million in total.

The model makes clear the importance of the availability of wood in terms of type, location and time. Locating facilities is problematic if the location of the available wood of a required type is changing over time. One issue involves how to interpret wood availability. The constraint is written as an inequality, implying that capacity plans can be chosen that do not use the available wood. However as observed earlier, the AAC of the harvesting model is really an “ARC.” If the AAC for one species is not used, this can not only affect future supply of that species, but also, given the mixed nature of the wood in many stands, can also affect the available supply of other species. If the wood availability constraint is treated as an equality, this implies that the wood supplies computed in the forest plan dictate the amount of capacity installed and to some extent the transportation solutions chosen.

**Discussion**

The purpose of the paper has been to raise questions about the interaction between the definition of the forest resource and...
the installed capacity in the forest industry. In mining, the very definition of the resource requires a coordinated plan encompassing both capacity and mining. For the most part, this approach is absent in forestry, where the resource is defined with little regard to its economic exploitation. Alternative approaches are possible.

One is an agricultural model with relatively constant supply and transportation costs using plantation forestry. Murphy et al. [20] discuss such a situation in the Pacific Northwest. To a certain extent, the U.S. South already works on such a model.

Another approach is a mining model in which the capacity is put in place over a relatively short time to exploit the resource efficiently. Such an approach has been discussed in coastal British Columbia [14], where a more explicit approach to the old-growth forests may well make sense. It is also to a certain extent implicit in actions dealing with the mountain pine beetle [21]. However, a mining model may also make some sense in regions where the current age-class distribution does not correspond to a regulated condition or where growth rates are so low that regulated forests cannot justify the scale of operations required for efficient use of capital and labour. In such situations, as in mining, sustainability implies ensuring that present benefits are shared with future generations. This implies a plan in place for biodiversity, watersheds, ecosystems, and communities.

If forest management is to be carried out extensively, then attention must be paid to the capacity and transportation issues at the time that the forest management plan is defined. Given that there is nothing in the forest planning model to constrain cash flows, even an optimized capacity plan may contain substantial periods with negative cash flows. This may work in a model, but not in real life. This suggests that forest management must be considered with specific attention to plans for industry capacity and transportation. Otherwise, there are very real risks that forest management plans may lead to economically unsustainable industry cash flows.

REFERENCES