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Forest Fibre Network Design with Multiple Assortments: a case study in Newfoundland

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Draft

9 **ABSTRACT**

10 The Canadian forest industry is facing several challenges including high fibre cost, decline in
11 commodity profitability and low investment levels at relatively old manufacturing plants. To
12 enable transformation of the industry, innovations are needed to develop value-added products
13 and to shift to an efficient integrated value chain. In this regard, improved logistics for better
14 handling of raw material, forest biomass utilization, and use of new technologies are some
15 promising avenues. In this paper, we propose a generic value chain model which includes
16 locating new sorting yards and biorefineries maximizing the overall profit of the value chain.
17 This integrated planning problem deals with strategic decisions including investments in new
18 facilities and technologies, and tactical decisions comprising backhaul transportation and fibre
19 flows across the value chain. To solve such a problem, we developed a mixed integer
20 programming model to design the forest value chain network. This model is used in an industrial
21 case study in the province of Newfoundland, Canada. We have generated and analyzed 32
22 scenarios evaluated on 12 predefined key performance indicators. The results show that
23 collaboration through backhauling, common terminals, and new assortments are important
24 opportunities to improve the profitability and efficiency of the value chain. The potential
25 improvement over the current situation is as high as 23% considering the aforementioned
26 actions.

27

28 *Key words: Forest biomass, value chain design, backhaul transportation, sorting yards,*
29 *integrated strategic and tactical planning.*

INTRODUCTION

In recent years, the forest industry crisis has had significant economic and social consequences. Several studies have investigated the causes and effects of these crises on the Canadian forest industry (Mockler and Fairbairn 2009; Mockler and Robichaud 2011). These studies show that the crisis in the industry has been provoked by a rapid decline in commodity demand, the volatile exchange rate of the Canadian dollar as well as strong competition from Asian companies. To deal with the aforementioned challenges, the industry should first stabilize its market conditions, then smoothly transform along four distinct lines: These are market development, operational efficiency, business process change and new product development (Natural Resources of Canada (A) 2016). Among them, new product development, in particular green energy from forest biomass, has been accentuated recently. Such development requires network redesign to introduce new facilities and technologies into the supply chain.

It is often more difficult to redesign a network than to design one from start. There is a need to consider the ongoing operations and to ensure smooth transition between the two designs. Moreover, the reengineering process can become even more complex when there are several stakeholders with their own objectives who have run their operations for many years. In reality, this is often the situation that must be dealt with primarily. Hence, our goal is to develop a decision support tool for all transition phases. The tool first proposes improvement directions for current state of supply chain. Afterwards, it provides new network design for new transformed industry.

To propose improvement strategies, it is essential to have insights about the entire forest supply chain. D'Amours et al. (2008) presented a global view of Canadian forest supply chain. They characterized the forest supply chain, in particular the Canadian one, as an integrated and

divergent supply chain. The forest wood flow starts with harvesting and then continues through sorting, transportation, storage and operating to convert to products comprised of lumber, pulp and paper, energy or new bio-products (Carlsson and Rönnqvist 2005). All final products are distributed to the market. Wood flow planning considering interactions between all business units was studied by Weintraub and Epstein (2005).

The sorting and transportation parts of wood flow have significant impacts on efficiency and economy of supply chain. Sorting activities help to reduce variability of supply to the mills that require wood supply with specific properties. Such supply strengthens the competitiveness of the industry since it makes possible high-quality products. In this regard, log sorting yards are among the improvement strategies for the forest economy (Alam et al. 2014). Several objectives including profit making, cost saving, risk reduction and an improved forest management economy could be achieved through strategic and operational planning of sorting yards (Dramm et al. 2004). In spite of its advantages, Carlgren et al. (2006) showed, for a case study, the introduction of demand for a specific log assortment will increase the transportation and sorting costs by up to 6%. However, they noted that backhaul transportation could reduce the cost by up to 25%. Hence, backhaul transportation plays a significant role in cost reduction.

There are several comprehensive studies on developing decision support systems for transportation planning with special consideration for backhauling (Carlsson and Rönnqvist 2007; Forsberg et al. 2005). Effective backhaul routes depend notably on stakeholders' cooperation. Palander and Väättäinen (2005), demonstrated a significant cost saving from backhauling combined with interenterprise collaboration in the Finnish forest industry.

Besides determining improvement directions, our tool has been developed to propose a smooth market transformation. This could happen in forest industry by invaluable forest biomass, which

76 consists of forest residues, non-merchantable woods, sawdust and other non-usable by-products.
77 These homogenous resources have been used for many years to provide forest industry energy.
78 However, with rising environmental concerns, the industry in such resources as a means of
79 producing renewable energies has increased. Frombo et al. (2009) provided a strategic decision
80 model to select an optimal energy-conversion technique that maximizes the selling profit minus
81 collection and transportation costs. Gunnarson et al. (2004) studied tactical planning for forest
82 bioenergy supply chain in which they satisfied the yearly contract-based energy demands. A
83 comprehensive study by Shabani et al. (2013) reviewed all recent researches on forest biomass
84 value chain optimization for bioenergy production.

85 Furthermore, forest residues are a great alternative to produce biofuels and bio-products because
86 of their wide geographical distribution and availability. Ekşioğlu et al. (2009) developed a mixed
87 integer programming (MIP) model for biorefinery supply chain producing ethanol from
88 agriculture and woody biomass. They proposed a network design for biorefinery location
89 coordinated with harvesting, sorting, transporting and processing decisions. Kim et al. (2011)
90 considered a forest supply chain comprising forest, potential location for biofuel plants and
91 market with objective of determining number, location and size of biofuel plants as well as
92 logistic planning. They performed a sensitivity analysis showing the significant effect of demand
93 variation on network design and profitability.

94 Integration of bioenergy and biofuel value chain in forest industry has been studied by Cambero
95 et al. (2014). The authors proposed a multi-period optimization model to decide the right period
96 for facility opening considering procurement planning. However, real integration in supply chain
97 consists in considering all existing partners. Troncoso et al. (2015) compared the integrated
98 forest value chain planning versus decoupled planning for a Chilean case study. The authors

reported that the net present value of value chain increased up to 5% when the proposed integrated solution is implemented.

Feng et al. (2010) clarified the potentiality of integrated forest biomass value chain. The paper proposed a general mathematical programming model to locate new biorefinery, assign technologies to them and allocate resources. New technology could develop in green field sites or existing mills. Dansereau et al. (2012) considered a pulp and paper mill which has facilities for biorefinery products. They considered manufacturing flexibility methodology to reduce the risk of assessing new technologies.

In this paper, we followed the concept of an integrated forest supply chain of Feng et al. (2010) in a more comprehensive way. The main decisions we consider are a) to locate value-adding facilities including biorefineries and sorting yards b) to assign technology and capacity to biorefineries c) to allocate resources to existing and new facilities d) to plan the logistics of supply chain considering transportation, sorting and operating and finally f) to consider the possibility of collaboration between industrial partners including backhaul transportation. Our general problem is motivated by a specific case of the forest industry in the province of Newfoundland, Canada. We propose an MIP model to investigate the aforementioned problem. All required information is collected from stakeholders in the province and FPInnovations, a Canadian non-profit organization in forestry research. The results of this project are reported in the Centre for Forest Science and Innovation of Newfoundland to be utilized as a guideline for industry improvement and competitiveness policies. The main contributions of the paper are the proposed model and its practical test in a real industrial case study setting.

The outline of the paper is as follows: Section 2 gives the problem description. Then the detailed case study is described in Section 3. Section 4 reports the results based on a set of designed

122 scenarios. Finally, we provide some concluding remarks.

123 **PROBLEM FORMULATION AND MATHEMATICAL MODEL**

124 Forest supply chain comprises four main entities: the forest, pulp and paper operation units,
125 wood-manufacturing units to produce lumber, panel and engineering wood, and transformation
126 units (Lehoux et al. 2012). Each of these entities has its own business plan to maximize its
127 revenue and profit; however, they are all interconnected (Figure 1). Manufacturing plants are
128 connected to the forest either directly or through terminals. Sawmills provide intermediate
129 products for pulp and paper mills and transformation mills. Finally, the products are delivered to
130 the market through distribution centres. A short description of each entity is provided in the
131 following.

132 *Forest-* Canada has the second largest forest in the world with 396 million hectares. There are 35
133 different economic important species. Forests and their industries play a vital role in the
134 Canadian economy, society and environment. They support one million jobs, i.e., 5.6 % of the
135 total employment of the country (Natural Resources of Canada (B) 2016).

136 *Terminal-* Terminals are in-transit yards for logs from the forest and before their arrival in mills.
137 They can be used as sorting yards, stock-yards or merchandizing yards (Lehoux et al. 2012).
138 Terminals provide a great opportunity for backhaulage for all stakeholders in the network and
139 can extensively increase the existing value of fibre in the network by allocating the right log to
140 the right mill with a minimum cost.

141 *Sawmill-* Products and by-products of sawmills have a crucial role in the efficiency of the entire
142 forest supply chain. Wood chips produced in the sawing process are utilized as raw material for
143 pulp and paper mills. Moreover, bark, sawdust, and shavings are used as feed for new
144 transformation processes.

Pulp and paper mill- An important part of the industry is the pulp and paper industry. However, the rise of electronic media and the steep decline in paper-based products has affected the main economic contributors of the forest industry. In this regard, their collaboration in the transformation of Canadian forest industry has dramatically increased.

Transformation unit- They are new facilities to start industry transformation. Several processes including extraction, combined heat and power, organic ranking cycle, pelletization, fermentation, and lignin precipitation could be employed at these units to produce biofuels, biochemicals, biodegradable plastics, personal care products and industrial chemicals from forest biomass. Among aforementioned processes, pelletization is a mature one with high yield. Moreover, the stable market of pellets, motivates investors towards such a low-risk investment option. In this regard, we consider pelletization as the process of our transformation unit to be included in the value chain network.

2.1 Optimization model

We propose an MIP model to find an optimal design for a general forest supply chain considering existing stakeholders, potential terminals and pellet mills, and backhaul availability. The model aims to maximize the profit of the network while satisfying a set of constraints such as customer demand, forest supply and mill capacities, existing road network, etc. The following will present the exact formulation of the MIP model including sets and parameters definition, decision variables and constraints.

Defined and supporting sets for the developed model are described in the following.

P^R set of raw and intermediate products

P^F set of final products

P set of all product types $P = P^R \cup P^F$

- 168 S set of sort groups
- 169 F^P set of piles
- 170 F^C set of species
- 171 D set of districts
- 172 Z set of zones
- 173 O set of tenure holders
- 174 L^T set of potential terminal locations
- 175 L^E set of potential biorefinery locations
- 176 M^P set of existing manufacturing plants
- 177 N set of all network nodes $N = Z \cup M^P \cup L^T \cup L^E$
- 178 R^i set of existing and candidate processes for mill i
- 179 H set of hauling type
- 180 L^B set of backhaul routes

181 Here are some comments on set of sort groups and set of hauling types; We define four sort
182 groups comprising unsorted supply, sort base on wood species, sort base on wood species and
183 their utilization, i.e., sawlogs, studwoods (short sawlogs), pulpwoods and energy woods and sort
184 base on wood species, utilization and dimension. The model allows sorting at different places
185 from higher sort group to lower ones. Moreover, we classify different truck organization within
186 the set of hauling types.

187 **Supporting sets:**

- 188 I_{izo} set of forest areas indicated by district i , zone z and tenure holder o .

- 189 H_{ojh} set of hauling methods for woods belonging to o with truck type h to mill j .
- 190 P_{rj}^R set of all processes r at mill j .
- 191 P_{pr}^{R+} set of input products p to process r .
- 192 P_{pr}^{R-} set of output products p from process r .
- 193 W_{lf}^{FS} set of sorted pile f created from sorting pile l .
- 194 E_{foj}^{FF} flow of pile f from forest tenure o to mill j .
- 195 E_{foij}^{FM} flow of pile f of tenure holder o from mills i to j .
- 196 The parameters used to describe harvest areas, costs, values, production at mills, and capacities
- 197 are given below.
- 198 k_{izop} annual allowable cut of product p at forest block indicated by $(izo) \in I_{izo}$.
- 199 a_{fl}^{FS} proportion of sorted pile f at pile l .
- 200 f_i fixed cost to open new facility i .
- 201 v_{pj}^F unit selling value of final product p at the gate of mill j .
- 202 c_s^I unit harvesting cost for each sort group S .
- 203 c_{sj}^S unit sorting cost to group S at mill j .
- 204 c_{pr}^R unit processing cost of product p at process r .
- 205 c_{izoj}^{HI} unit transportation cost of any product from forest area indicated by $(izo) \in I_{izo}$ to mill j .
- 206 c_{ijh}^{HM} unit transportation cost of any product between mill i and j by truck type h .
- 207 c_{lh}^{ML} unit transportation cost for backhaul route l by truck type h .

- 208 a_{lfsj}^{ML} 1; if backhaul trip l picks up pile f with sort group S and owner o at supply point j .
- 209 b_{lfsj}^{ML} 1; if backhaul trip l delivers pile f with sort group S and owner o to demand point j .
- 210 u_{prq}^R yield of process r in producing product q while it is fed by product p .
- 211 k_r^{R+} max capacity of process r .
- 212 k_r^{R-} min capacity of process r .
- 213 k_{jh}^H transportation capacity of truck type h for mill j .
- 214 M a big value.
- 215 To avoid nonlinearity in modelling we assume the proportion of available products in each pile (a_{jl}^{FS}) is known. This value is estimated by average on proportion of available forest resources.
- 217 The decision variables used in the models are:
- 218 y_i^E 1; if biorefinery i is open, and 0 otherwise.
- 219 y_i^T 1; if terminal i is open, and 0 otherwise.
- 220 x_{izo}^A 1; if forest block indicated by $(izo) \in I_{izo}$ is assigned to mill j , and 0 otherwise.
- 221 x_{sizo}^{AP} percentage of harvesting in sort group S from forest block indicated by $(izo) \in I_{izo}$.
- 222 $x_{fsciojh}^{FF}$ flow of pile f with sort group S and species c from forest block indicated by $(izo) \in I_{izo}$
- 223 to mill j by truck type h .
- 224 $x_{fsciojh}^{MF}$ flow of pile f with sort group S and species c belong to owner o between mills i and j
- 225 by truck type h .
- 226 x_{lh}^{ML} backhaul flow l done by truck type h .

- 227 x_{jp}^E volume of final product p produced at mill j .
- 228 x_{fsoj}^S sorting amount of pile f with sort group S and wood owner o at mill j .
- 229 x_{psorj}^R volume of inputted product p with sorting group S and wood owner o to process r at mill
- 230 j .

231 Most of the decision variables are anticipation variables which are used to evaluate the strategic

232 decisions. As such, these anticipation decisions are not be operated. Instead, shorter-term tactical

233 and operational models will be used to find such operational decisions. Besides, the available

234 data is based on long-term allowable annual cut (AAC) models which essentially describe the

235 available volume per year. As these numbers are the same; it is possible to use only one time

236 period to make strategic decisions. Hence, we do not consider time horizon dimension for

237 decision variables.

238 The objective function is to maximize the profit (revenue from sales minus costs). The sales

239 value of final products is the revenue of the network. The included costs in the model are

240 harvesting, transportation, sorting, operating, and fixed cost to open new terminals and

241 biorefinery.

$$\begin{aligned}
 \text{Max } Z : & \sum_{p \in P^F} \sum_{j \in N} (v_{pj}^F x_{jp}^E) - \sum_{s \in S} \sum_{(izo) \in I_{20}} \sum_{p \in P^R} (c_s^I k_{izop} x_{sizo}^{AP}) - \sum_{(izo) \in I_{20}} \sum_{(foj) \in E_{foj}^{FF}} \sum_{s \in S} \sum_{c \in F^C} \sum_{h \in H} (c_{izoj}^{HI} x_{fsctzoh}^{FF}) - \\
 & \sum_{(foij) \in E_{foij}^{FM}} \sum_{s \in S} \sum_{c \in F^C} \sum_{h \in H} (c_{ijh}^{HM} x_{fscoijh}^{MF}) - \sum_{l \in L^B} \sum_{h \in H} (c_{lh}^{ML} x_{lh}^{ML}) - \sum_{f \in F^P} \sum_{s \in S} \sum_{o \in O} \sum_{j \in N} (c_{sj}^S x_{fsoj}^S) - \\
 & \sum_{(pr) \in P_{pr}^{R+}} \sum_{s \in S} \sum_{o \in O} \sum_{(rj) \in P_{rj}^R} (c_{pr}^R x_{psorj}^R) - \sum_{i \in L^T} f_i y_i^T - \sum_{i \in L^E} f_i y_i^E
 \end{aligned} \tag{1}$$

243 The model is subjected to a set of constraints for capacity constraint, fibre delivery constraints,

244 balance constraints, flow constraints and demand constraints.

245 **Capacity constraints:**

246 The first set of constraints, harvest capacity constraint, assures the sum of a percentage of
 247 harvested products in different sorting groups for each forest block should be less than one.

$$248 \quad \sum_{s \in S} x_{sizo}^{AP} \leq 1 \quad \forall (i, z, o) \in I_{izo} \quad (2)$$

249 The resource should satisfy mill demand; however each forest area may only be assigned to one
 250 mill (constraint set (3)).

$$251 \quad \sum_{j \in N} x_{izoj}^A \leq 1 \quad \forall (izo) \in I_{izo} \quad (3)$$

252 Constraint set (4) assures that only assigned forest area will be harvested.

$$253 \quad \sum_{s \in S} \sum_{z \in Z | (izo) \in I_{izo}} x_{sizo}^{AP} \leq \sum_{j \in N} x_{ioj}^A \quad \forall i \in D, o \in O \quad (4)$$

254 Constraint set (5) considers the restricted capacity of transportation of all transported products to
 255 or from a mill.

$$256 \quad \sum_{(foj) \in E_{foj}^{FF}} \sum_{s \in S} \sum_{c \in F^C} \sum_{(izo) \in I_{izo}} x_{fscizojh}^{FF} + \sum_{(foij) \in E_{foij}^{MF}} \sum_{s \in S} \sum_{c \in F^C} x_{fscioijh}^{MF} + \sum_{l \in L^B} \sum_{(foij) \in E_{foij}^{MF}} \sum_{s \in S} b_{lfsjoj}^{ML} x_{lh}^{ML} + \quad \forall j \in N, h \in H \quad (5)$$

$$\sum_{s \in S} \sum_{i \in N} \sum_{f \in P^F} \sum_{(foji) \in E_{foji}^{FM}} \sum_{c \in C} x_{fscioijh}^{MF} + \sum_{l \in L^B} \sum_{i \in N} \sum_{(foji) \in E_{foji}^{MF}} \sum_{s \in S} a_{lfsjoj}^{ML} x_{lh}^{ML} \leq k_{hj}$$

257 Flow constraints

258 The flow of wood in the network will start from the forest; therefore, all harvested resources
 259 should be directly forwarded from the forest to mills (constraint set (6)).

$$260 \quad \sum_{p \in P^R} k_{izop} x_{sizo}^{AP} - \sum_{(foj) \in E_{foj}^{FF}} \sum_{c \in F^C} \sum_{(ojh) \in H_{ojh}} x_{fscizojh}^{FF} = 0 \quad \forall (izo) \in I_{izo}, s \in S \quad (6)$$

261 Moreover, constraint set (7) permits all the decision variables related to the biorefinery to have
 262 the value 1 if the facilities are open. The same constraint exists for terminals.

$$\begin{aligned}
& \sum_{(foj) \in E_{foj}^{FF}} \sum_{(izo) \in I_{zo}} \sum_{s \in S} \sum_{c \in F^C} \sum_{(ojh) \in H_{ojh}} x_{fscizojh}^{FF} + \sum_{(foij) \in E_{foij}^{FM}} \sum_{s \in S} \sum_{c \in F^C} \sum_{(ojh) \in H_{ojh}} x_{fscioijh}^{MF} + \\
& \sum_{l \in L^B} \sum_{(foij) \in E_{foij}^{MF}} \sum_{s \in S} \sum_{h \in H} b_{lfsjoj}^{ML} x_{lh}^{ML} + \sum_{(lf) \in W_{lf}^{FS}} \sum_{s \in S} \sum_{o \in O} (a_{fl}^{FS} x_{jls o}^S) + \quad \forall j \in l^E \cup l^T \quad (7)
\end{aligned}$$

$$\begin{aligned}
& \sum_{(rj) \in P_{rj}^R} \sum_{(fr) \in P_{fr}^{R-}} \sum_{(pr) \in P_{pr}^{R+}} \sum_{s \in S} \sum_{o \in O} (u_{prf}^R x_{psorj}^R) + \sum_{(foji) \in E_{foji}^{FM}} \sum_{s \in S} \sum_{c \in C} \sum_{(oih) \in H_{oih}} x_{fscioijh}^{MF} + \\
& \sum_{l \in L^B} \sum_{(foij) \in E_{foij}^{MF}} \sum_{s \in S} \sum_{h \in H} a_{lfsjoj}^{ML} x_{lh}^{ML} + \sum_{f \in F^P} \sum_{s \in S} \sum_{o \in O} x_{jfs o}^S + \sum_{(pr) \in P_{pr}^{R+}} \sum_{s \in S} \sum_{(rj) \in P_{rj}^R} \sum_{o \in O} x_{psorj}^R \leq My_j^E
\end{aligned}$$

264 Balance constraints:

265 The balance constraints are defined to assure the equilibrium of inputs and outputs of each mill
 266 for different sorting piles. Constraint set (8) assures the balance of raw material and intermediate
 267 products in the format of different piles at mills. The input flow can be a flow from forest or
 268 mills (direct or backhaul), or the output of a sorting process or a process where we consider
 269 balance constraint for the intermediate product.

$$\begin{aligned}
& \sum_{(foj) \in E_{foj}^{FF}} \sum_{c \in C} \sum_{(izo) \in I_{zo}} \sum_{(ojh) \in H_{ojh}} x_{fscizojh}^{FF} + \sum_{(foij) \in E_{foij}^{FM}} \sum_{c \in C} \sum_{(ojh) \in H_{ojh}} x_{fscioijh}^{MF} + \\
& \sum_{l \in L^B} \sum_{(foij) \in E_{foij}^{MF}} \sum_{h \in H} b_{lfsjoj}^{ML} x_{lh}^{ML} + \sum_{(lf) \in W_{lf}^{FS}} \sum_{o \in O} (a_{fl}^{FS} x_{jls o}^S) + \quad \forall j \in N, f \in F^P, \quad (8) \\
& \sum_{(pr) \in P_{pr}^{R+} \& (fr) \in P_{fr}^{R-}} \sum_{o \in O} \sum_{(rj) \in P_{rj}^R} (u_{prf}^R x_{psorj}^R) - \sum_{(foji) \in E_{foji}^{MF}} \sum_{c \in C} \sum_{(oih) \in H_{oih}} x_{fscioijh}^{MF} - \\
& \sum_{l \in L^B} \sum_{(foji) \in E_{foji}^{MF}} \sum_{h \in H} a_{lfsjoj}^{ML} x_{lh}^{ML} - \sum_{o \in O} x_{jfs o}^S - \sum_{(fr) \in P_{fr}^{R+}} \sum_{o \in O} \sum_{(rj) \in P_{rj}^R} x_{psorj}^R = 0
\end{aligned}$$

271 The balance constraint for final product at mill is formulated in constraint set (9).

$$\sum_{(fr) \in P_{fr}^{R+} \& (pr) \in P_{pr}^{R-}} \sum_{(jr) \in P_{jr}^R} \sum_{s \in S} \sum_{o \in O} (u_{frp}^R x_{jsorj}^R) - x_{jp}^E = 0 \quad \forall j \in N, p \in P^F \quad (9)$$

273 Demand constraints

274 In our modelling, each process has a minimum and maximum production range capacity
 275 (constraint (10)). For the energy plants, this constraint depends on the existence of them in our
 276 network structure (constraint 11).

277

$$k_r^{R+} \leq \sum_{(fr) \in P_{fr}^{R+}} \sum_{s \in S} \sum_{o \in O} x_{fsorj}^R \leq k_r^{R-} \quad \forall (rj) \in P_{rj}^R \quad (10)$$

278

$$k_r^{R+} y_j^E \leq \sum_{f \in F^R} \sum_{(fr) \in P_{fr}^{R+}} \sum_{s \in S} \sum_{o \in O} x_{fsorj}^R \leq k_r^{R+} y_j^E \quad \forall r \in R, j \in L^E \mid (rj) \in P_{rj}^R \quad (11)$$

279 **Variable definition constraints**

280 Finally, variables are defined in constraint set (12) and (13).

281

$$y_i^E, y_i^T, x_{izoj}^A \in \{0,1\}, x_{sizo}^{AP} \in \{0,1\} \quad (12)$$

282

$$x_{fscizojh}^{FF}, x_{fscioijh}^{MF}, x_{lh}^{ML}, x_{jp}^E, x_{jfsO}^S, x_{fsorj}^R \geq 0 \quad (13)$$

283 **CASE STUDY**

284 Newfoundland is the insular portion of the Canadian province of Newfoundland and Labrador
285 situated in the North Atlantic Ocean. It has two million ha of productive forestland, within 18
286 districts, available or partially available for harvest. The lands are 96% owned by the public and
287 4% by the private sector. The primary commercial species are black spruce (*Picea mariana*) and
288 balsam fir (*Abies balsamea*). There are four stakeholders in operation: Corner Brook Pulp and
289 Paper Limited (capacity 700,000 m³/yr), Burton’s Cove Lumber Limited (capacity 70,000
290 m³/yr), Cottle’s Island Lumber (capacity 40,000 m³/yr), and Sexton Lumber (capacity 180,000
291 m³/yr) respectively from west to east. The final products of the mills are mainly conventional
292 forest products, including lumber, pulp and paper, and energy. Corner Brook Pulp and Paper
293 holds timber tenure of 29% of the total public forestlands that has been called Kruger tenure.
294 This means other stakeholders are not permitted to harvest Kruger tenure (Sustainable Forest
295 Managment 2013). They have annual agreements with the government that allow them to harvest
296 specific areas.

297 A Newfoundland forest map is depicted in Figure 2. The green blocks in the picture are harvest

areas of $2 \text{ km} \times 2 \text{ km}$ size. Newfoundland has 5,888 of such blocks for each, district number, location, timber tenure holder, harvest capacity and fibre attributes are known by the Newfoundland Centre for Forest Science and Innovation. However, such detailed information is not necessary for a strategic tactical planning problem. Hence, we aggregate forest blocks to a larger size called zone as a forest management unit. The same information for blocks is available for each of 520 zones. Afterwards, we identify each harvest area with its district number, zone number and tenure holder.

The transportation cost between all network nodes is calculated by FPInterfaceTM. Information comprising supply, harvesting and purchasing cost, yield of process and operation cost is collected from each stakeholder. All values (revenues) and costs are evaluated as sold at mill gate.

Fibre wood availability is one of the most challenging problems in this supply chain, particularly for sawmills with their restricted timber tenure. Two reasons are the cause of this problem. First, Newfoundland has a very acid soil with low fertility, which means large and vast supply areas. Second, mills do not receive the quantity and quality of supply they require. Sorting yards with the goal of delivering the right fibre to the right mill at the right time could significantly improve current situation.

On the other hand, high transportation costs as well as environmental concerns are two other significant problems for Newfoundland forest supply chain. The large resource distribution increases the transportation distance. The west of the insular area is covered by balsam fir which is valuable feedstock for Corner Brook Pulp and Paper; and conversely, the eastern part of the island is covered by black spruce, a valuable raw material for sawmills. Moreover, transportation in Newfoundland is operated by several independent organizations under different agreements.

As a consequence, the supply delivery to Corner Brook Pulp and Paper is restricted to drivers from a particular organization. This condition severely limits opportunity for collaboration in the form of backhauling transportation.

Backhaul transportation could be a beneficial option to demonstrate the impact of collaboration, to reduce transportation costs and greenhouse gas (GHG) emissions. We have designed three sets of backhaul routes depicted in Figure 3. Each backhaul route characterizes the supply and delivery nodes as well as the hauled products and their owner. The total saving in backhaul transportation declared in the figure is calculated by the reduction in empty driving distances.

Moreover, we calculate the reduction in GHG emissions by using backhaul transportation in equation (14) (Lakshmanan and Han 1997). The equation requires distance travel ($m^3 \times km$), fuel consumption ($\frac{gallon}{(100km)(m^3)}$); and fuel specific factor ($8.887 \times 10^{-3} \frac{metric\ tons}{gallon}$) to calculate metric tons of CO2 emissions.

$$GHG = Distance\ travel \times fuel\ consumption \times fuel\ specific\ factor \tag{14}$$

The Newfoundland stakeholders are always searching for new products, processes, and markets to increase their profit margin. Investigation of their current state and the availability of wood energy in the forest have identified that new biorefinery are ideal options for improving their profitability (Melendez Esquivel 2015). The new process could be installed either in green field site or existing mills.

The case study in Newfoundland is a very good test for our proposed model. Twenty potential locations for terminals and one potential location for a biorefinery are considered (Figure 4). These locations represent large crossings in the road network and are identified together with government representatives in collaboration with the stakeholders. Moreover, to evaluate the

effect of each of the aforementioned actions we develop different scenarios. Each scenario is optimized by the model and analyzed.

The scenarios are generated through a combination of assumptions. The assumptions are: 1) allowable wood allocation in forest can be shared between all stakeholders; 2) accessibility of sawmills to supply in the Kruger tenure; 3) possibility of using backhaul availability; 4) terminals can be used; 5) biorefineries can be used. Assumption (1) gives the model the possibility to allocate a harvest zone to more than one stakeholder. It is provided to model by relaxing constraint set (3). Assumption (2) allows sawmills to harvest and transport from forest zones located in the Kruger tenure to mills. Modification in the matrix of flows permits such wood flows. Backhaul availability, terminals and a pellet mill are applied to model by their decision variable whether they are zero or not. It is worth mentioning that assumption (1) - (3) could be used directly if the stockholders accept collaboration. Hence, any scenario that includes these assumptions represents collaboration concept.

The matrix of the scenarios is provided in Table 1. Scenario (1) presents the current situation of the network where none of the aforementioned assumptions exists. The other scenarios, however, are current situations considering one or several assumptions. For instance, in scenario 18, we allow the optimization model to allocate a forest zone to different stakeholders, and to have terminal opening opportunity. The other scenarios are interpreted in the same way considering its active assumptions.

RESULTS

The model is implemented in the modelling language AMPL using CPLEX 12.0 as a solver. For all numerical tests, we have used a standard PC with a 2.6 GHz processor and 42.0 GB RAM. The size of each scenario, its solution time and its gap using CPLEX directly are presented in

Table 2. The number of binary and linear variables as well as constraints is provided for each scenario. A restricted solution time of 1,800 seconds is considered for each problem. The gap determines the difference between best integer solution and best bound (from the LP relaxation) divided by the best bound. All problems were solvable with a maximum gap of 0.5%.

For each scenario, we report on a set of key performance indicators (KPI). These KPIs, defined in Table 3, demonstrate how effectively each mill achieves the business objective and have been identified together with the stakeholders. They are reported for each stakeholder and for each scenario. KPIs RevInt and RevFin calculate respectively the revenue from selling Intermediate and final products at mill gates. KPIs 3 to 9 demonstrate strategic and tactical costs. The profit and total delivered product volume to each mill are calculated by KPIs TotalProfit and TotalIn, respectively. The KPI Profit/In represents the profit per one m^3 of the proceeded supply. Finally, KPI GHG indicates the saving in GHG emissions using backhauling.

Table 4 reports total revenue of selling products, fixed cost, tactical cost and profit in millions of CAD dollars. Moreover, it reports total volume incoming product in million cubic metres. The profit per one m^3 of incoming product as a key comparator of the scenarios is calculated in Profit/In column. The GHG column represents reduction of GHG emissions of all stakeholders. The model provides the detailed tactical information including the flow of products, the amount of sorted and operated product and the amount of backhauling for each stakeholder. It is worth mentioning that, tactical cost is the sum of harvesting, purchasing, transporting, sorting and operating costs.

As the table shows, in all of the scenarios, the optimization model supplies the stakeholders up to their maximum requirements, hence the total revenue is almost equal for all scenarios. The revenue of stakeholders will increase in the scenarios which open a pellet mill. For instance, the

total revenue of scenarios s_1 and s_{18} has a difference of around \$6.7 million which is principally created by the opening of the pellet mill. On the other hand, the flow of products within the network will reduce in all of the scenarios compared to the base case and according to reduction in tactical costs. Harvesting cost primarily depends on two factors including the accessibility of sawmills to Kruger tenure and having a pellet mill. If the mill demands have not been satisfied by harvesting operation, they will purchase wood supply from other mills.

As regards value creation, the model suggests the sorting opportunity for all scenarios to create higher value from the fibre. In all scenarios, the solutions supply stakeholders up to their maximum volume requirement; however different total profits are reported. This shows two key points: the first is, even in the base case scenario, the supply chain has the ability to provide secure fibre for all stakeholders; second, with the same input and more collaboration all stakeholders could generate more profit. Revenue, cost and profit for all scenarios are compared in Figures 5, 6 and 7, respectively. Comparison of Profit/In for different scenarios in Figure 7 presents a potential saving of 23.06% for the entire supply chain which could be created only by collaboration between stakeholders.

The overall localization decisions of the model are to open one terminal in the west of Newfoundland or the one in the east central region (Figure 8). The terminal in the West will facilitate the transportation to Corner Brook Pulp and Paper by their hauling fleets, and from that terminal to all stakeholders, the possibility of backhauling by other drivers will be provided. Moreover, in all scenarios with the possibility of wood exchange, all harvested pulp logs will be delivered directly to the terminal and then to Corner Brook Pulp and Paper. The terminal located in East is preferable if sawmills have accessibility to Kruger tenures. In this way, the decision supporting tool suggests harvesting the centre of Newfoundland and delivering to terminals in

the centre, and then distributing the products. The pellet mill is a profitable decision when sawmills have access to Kruger tenure, otherwise the restriction on resources will prevent such investment. The location of selected terminals is also in accordance with the expectations of all stakeholders.

CONCLUDING REMARKS

We have developed an MIP model to design a forest biomass value chain with special consideration of fibre value creation. Our developed model covers important strategic and tactical decisions at the same time. The strategic decisions include locating new terminals and a pellet mill. The network flows, harvesting, purchasing, transporting and sorting costs are considered in the model to support a sustainable strategic decision. The backhauling transportation opportunity is considered to reduce cost and GHG emissions.

Our generic model was validated with a real case study in the context of the Newfoundland forest industry and has provided guidelines for this supply chain to progress. Two special conditions of the case study including truck hauling regulation and timber tenure holders have considerable effect on profitability of the industry. Moreover, the significant effect of collaboration on network profitability has been reported.

Our developed optimization model has the ability to consider a new bio-process in its modelling. However, a comprehensive market study is required to design a good product-process portfolio. A fact in such a new market is the uncertainty about availability of resources, performance of new processes and the market of new products. In this regard, uncertainty consideration in such areas could be very interesting to study and to compare with the current findings. Moreover in the new designed value chain the individual stakeholder saves differently, hence a study on sharing profit mechanisms could introduce an applicable future work.

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Table 1. Developed scenarios based on the five defined assumptions

Assumption* scenario	1	2	3	4	5
S1	-**	-	-	-	-
	√**				
S2	*	-	-	-	-
S3	-	√	-	-	-
S4	-	-	√	-	-
S5	√	√	-	-	-
S6	-	√	√	-	-
S7	√	-	√	-	-
S8	√	√	√	-	-
S9	-	-	-	√	-
S10	√	-	-	√	-
S11	-	√	-	√	-
S12	-	-	√	√	-
S13	√	√	-	√	-

S ₁₄	-	√	√	√	-
S ₁₅	√	-	√	√	-
S ₁₆	√	√	√	√	-
S ₁₇	-	-	-	-	√
S ₁₈	√	-	-	-	√
S ₁₉	-	√	-	-	√
S ₂₀	-	-	√	-	√
S ₂₁	√	√	-	-	√
S ₂₂	-	√	√	-	√
S ₂₃	√	-	√	-	√
S ₂₄	√	√	√	-	√
S ₂₅	-	-	-	√	√
S ₂₆	√	-	-	√	√
S ₂₇	-	√	-	√	√
S ₂₈	-	-	√	√	√

S ₂₉	√	√	-	√	√
S ₃₀	-	√	√	√	√
S ₃₁	√	-	√	√	√
S ₃₂	√	√	√	√	√

*Assumptions are as follows:

1) Allowable wood allocation in forest between all stakeholders; 2) accessibility of sawmills to Kruger tenure; 3) backhaul availability; 4) terminals opening; 5) biorefinery opening.

**Hyphen determines that assumption in the related scenario is inactive

***Check mark determines that assumption in the related scenario is active

Table 2. Size of each scenario using CPLEX directly

scenario	binary variables	linear variables	constraints	solution time(s)	gap(%)
S ₁	13,900	21,345	16,780	0.53	0.00
S ₂	1,520	21,345	3,205	0.22	0.00
S ₃	13,900	21,823	17,038	0.66	0.00
S ₄	13,900	21,385	16,788	0.52	0.02
S ₅	1,580	21,823	3,463	0.16	0.00
S ₆	13,900	21,930	17,054	0.94	0.04
S ₇	0	21,385	1,693	0.02	0.00
S ₈	21	176,036	7,355	21.40	0.00
S ₉	13,920	162,193	32,768	1800.08	0.13
S ₁₀	20	162,193	7,273	11.67	0.00
S ₁₁	13,920	162,811	32,846	1800.00	0.18
S ₁₂	13,920	167,349	32,772	132.38	0.11
S ₁₃	12,000	16,281	19,271	14.59	0.00
S ₁₄	13,920	171,843	32,854	221.05	0.12
S ₁₅	20	167,349	7,277	24.12	0.22

S ₁₆	20	171,843	7,299	1711	0.17
S ₁₇	13,901	31,410	21,822	1.4	0.00
S ₁₈	1	13,410	6,227	0.69	0.00
S ₁₉	13,901	32,028	22,106	1.36	0.79
S ₂₀	13,901	31,450	21,830	1.17	0.00
S ₂₁	2,101	32,028	8,531	1.39	0.00
S ₂₂	13,901	32,108	22,122	1.33	0.17
S ₂₃	1	31,450	6,235	1.48	0.00
S ₂₄	1	32,108	6,447	0.64	0.02
S ₂₅	13,921	166,246	33,318	1800.08	0.46
S ₂₆	21	166,246	7,323	17.25	0.00
S ₂₇	13,921	167,004	33,422	1801.11	0.16
S ₂₈	13,921	171,402	33,322	78.62	0.08
S ₂₉	12,521	167,004	19,847	17.04	0.00
S ₃₀	13,921	176,036	33,430	834.93	0.05
S ₃₁	21	171,402	7,327	35.04	0.00
S ₃₂	21	176,036	7,355	22.22	0.00

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Table 3. Key performance indicator definition

Item	KPI	Description
1	RevFin	Revenue from selling products
2	RevInt	Revenue from selling products
3	FixCost	Fixed cost to open terminals or pellet mill
4	HvCost	Harvesting cost for each sort group
5	PurCost	Purchasing cost for each sort group
6	SortCost	Sorting cost for each sort group
7	OperCost	Operating cost for each sort group
8	TransCost	Transportation cost for each sort group
9	TotalProfit	Total profit (revenue – costs)
10	TotalIn	Total m ³ input to mills
11	Profit/In	Profit per m ³ of input products at each mill
12	GHG	Tonnes of GHG emissions reduction by backhaul transportation

Table 4. The optimization result for each of the scenarios (revenue, costs and profit are in million CAD)

Scen	Total Revenue	FixCost	Tactical cost	TotalProfit	TotalIn	Profit/IN	GHG
s ₁	197.32	0.00	129.02	68.30	1.45	47.09	-
s ₂	196.78	0.00	128.34	68.44	1.44	47.43	-
s ₃	195.36	0.00	126.71	68.64	1.45	47.29	-
s ₄	194.55	0.00	122.16	72.39	1.43	50.66	745.6
s ₅	189.23	0.00	117.12	72.11	1.26	57.46	-
s ₆	193.86	0.00	117.56	76.30	1.43	53.39	731.2
s ₇	194.52	0.00	122.00	76.38	1.43	50.74	750.3
s ₈	191.04	0.00	114.92	76.12	1.31	57.95	498.3
s ₉	199.28	0.50	130.26	69.02	1.53	45.24	-
s ₁₀	195.67	0.50	123.75	71.92	1.42	50.55	-
s ₁₁	198.36	0.50	129.20	69.16	1.53	45.18	-
s ₁₂	194.55	0.00	122.16	72.39	1.43	50.66	745.6
s ₁₃	192.32	0.50	119.60	72.72	1.32	55.09	-
s ₁₄	193.86	0.00	117.56	76.30	1.43	53.39	731.2
s ₁₅	195.68	0.50	122.68	59.26	1.17	50.71	474.7

S ₁₆	190.97	0.00	114.86	76.12	1.31	57.95	498.3
S ₁₇	197.54	0.00	129.24	68.30	1.45	47.09	-
S ₁₈	203.99	1.00	132.71	71.28	1.45	49.28	-
S ₁₉	195.36	0.00	126.72	68.65	1.45	47.36	-
S ₂₀	194.55	0.00	122.16	72.39	1.43	50.66	745.6
S ₂₁	189.29	0.00	117.18	72.11	1.26	57.46	-
S ₂₂	194.06	0.00	117.76	76.30	1.43	53.39	731.2
S ₂₃	194.52	0.00	122.00	76.38	1.43	50.74	750.3
S ₂₄	190.95	0.00	114.83	76.12	1.31	57.95	498.3
S ₂₅	199.28	0.50	130.26	68.87	1.54	45.24	-
S ₂₆	195.79	0.50	123.87	71.92	1.42	50.55	-
S ₂₇	198.18	0.50	129.01	69.17	1.53	45.35	-
S ₂₈	194.55	0.00	122.16	72.39	1.43	50.66	745.6
S ₂₉	192.46	0.50	119.74	144.89	1.32	55.09	-
S ₃₀	193.92	0.00	117.63	76.30	1.43	53.40	731.2
S ₃₁	195.68	0.50	122.68	60.14	1.44	50.71	474.7
S ₃₂	191.04	0.00	114.92	76.12	1.31	57.95	498.3

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Figure 2. Map of Newfoundland forest industry

Figure 3. Potential location for terminals (yellow points) and pellet mill (purple point), the mills are depicted by black points (map is taken from FPInterfaceTM)

Figure 4. The possible backhaul routes: (a) Newfoundland's principle backhaul route without empty driving between Corner Brook Pulp and Paper (CBPPL) and Sexton Lumber. (b and c) Backhaul routes with more full load trips rather than empty driving between Corner Brock pulp and paper Ltd, Sexton Lumber and an open terminal.

Figure 5. Sum of revenue for selling products. The orange line in all figures is the total revenue for base case scenario. The scenarios are compared in four categories: (a) scenarios without terminal and pellet mill opening assumptions, (b) scenarios with terminal opening assumption, (c) scenarios with pellet mill opening assumption, and (d) scenarios with terminal and pellet mill opening assumptions.

Figure 6. Total network cost for each scenario. The brown line in all figures is total cost for base case scenario. The scenarios are compared in four categories: (a) scenarios without terminal and pellet mill opening assumptions, (b) scenarios with terminal opening assumption, (c) scenarios with pellet mill opening assumption, and (d) scenarios with terminal and pellet mill opening assumptions. The percentage on top of all bars determines the difference between the scenario and the reference line.

Figure 7. Total network profit and profit/m3 for each scenario. The orange and green lines in all figures are total profit and profit/m3 for base case scenario. The scenarios are compared in four categories: (a) scenarios without terminal and pellet mill opening assumptions, (b) scenarios with terminal opening assumption, (c) scenarios with pellet mill opening assumption, and (d) scenarios with terminal and pellet mill opening assumptions. The percentage on top of all bars determines the difference between the scenario and their corresponding reference line.

Figure 8. Selected facilities location in different scenarios (map is taken from FPInterfaceTM)