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Glenn Weigel,
Sophie D'Amours,
Alain Martel
and
Paul Watson

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Research Consortium on e-Business in the Forest Products Industry (FORAC),
Network Organization Technology Research Center (CENTOR),
Université Laval, Québec, G1K 7P4, Canada

A Strategic Planning Model for Maximizing Value Creation in Pulp and Paper Mills

Glenn Weigel [I,II,1], Sophie D'Amours [II,2], Alain Martel [II,3], Paul Watson [I,4]

[I] Pulp and Paper Research Institute of Canada (PAPRICAN), 3800 Wesbrook Mall, Vancouver, BC, Canada, V6S 2L9

[II] Consortium de recherche FOR@C, CENTOR, Université Laval, Québec, QC, Canada, G1K 7P4

Abstract:

The research leading to the modeling framework presented in this paper was motivated by the need to provide Canadian pulp and paper producers with a means of maximizing the value created from available fibre supplies. The proposed approach involves finding optimal strategies for partitioning fibre supplies into grades, allocating fibre grades to processes and end-products, selecting appropriate production technologies and capacities, and establishing end-product range compositions within the context of an integrated pulp and paper mill. These strategies are elaborated with a generic mixed-integer programming model which can be solved using commercial optimization software. Three test case scenarios are used to validate the model and illustrate how it can be applied in strategic decision making under specific fibre supply and market demand constraints.

Keywords:

Manufacturing centre design, Pulp and paper industry, Fibre supply sorting strategies, Mathematical programming.

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[1] Corresponding author. Email: gweigel@paprican.ca
[2] Email: alain.martel@osd.ulaval.ca
[3] Email: sophie.damours@gmc.ulaval.ca
[4] Email: pwatson@paprican.ca

1 Introduction

The pulp and paper industry is a major contributor to the Canadian economy. In 2003, the industry produced nearly 46 million metric tonnes of products which had a combined value of more than 33 billion dollars[1,2]. This represented approximately six percent of the value of all products manufactured in Canada in 2003[2]. Nearly two thirds of Canada's annual pulp and paper production is exported, and Canada is the world's leading exporter of market pulp and newsprint[2,3]. The industry is, however, facing several significant challenges. Market globalization, advances in electronic media technologies, volatile commodity prices, and chronic supply and demand cyclicality are all having major impacts on the business environment. At the same time, evolving customer demands and a trend towards product specialization are increasing the importance of product quality and consistency, and cost factors and environmental pressures are placing ever tighter constraints on fibre supplies. Martel *et al.* (2005) present a detailed discussion of supply chain challenges facing the Canadian pulp and paper industry. Together, these challenges are making it increasingly critical that Canadian pulp and paper producers find new ways to maximize the value created from available fibre supplies.

Pulp and paper production itself poses an additional challenge. Pulp and paper quality is governed by processing conditions on one hand, and wood and fibre properties such as fibre length, fibre transverse dimensions, microfibril angle and chemical composition on the other. Natural variations in wood and fibre properties leave producers with the considerable challenge of producing products of consistent quality from raw materials of highly variable quality. Fundamental changes to the nature of the Canadian fibre supply are making it increasingly important that producers maximize the efficiency with which fibre types are allocated to process streams.

The model presented in this paper provides a mathematical framework for addressing these challenges according to two parallel strategies. The first of these involves managing the flow of materials through the value chain in such a way that fibre types are matched with the processes and end-products to which they are best suited. The second involves tailoring the end-product

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[1] Pulp and Paper Products Council. http://www.pppc.org.
[2] Statistics Canada. http://www.statcan.ca.
[3] Fisher International. http://www.fisheri.com.

range to take maximum advantage of the existing market conditions and the properties of the available fibre supply. The model also links the selection of production technologies and capacities to the processing requirements imposed by these strategies.

The use of mathematical modeling techniques to solve value chain optimization problems of this type is well established. Shapiro (2001) presents an overview of value chain modeling applications in many industries, and Rönnqvist (2003) presents a review of modeling applications specific to the forest products industry. Martel (2005) proposes an integrated modeling framework incorporating most of the supply chain design formulations published to date, and Vila *et al.* (2005) propose a supply network design methodology specific to divergent process industries. A few value chain design models have also been developed specifically for the pulp and paper industry. Benders *et al.* (1981) detail how International Paper's network design problems are analyzed and solved using mathematical programming models. Philpott and Everett have been responsible for the development of three separate planning models known as PIVOT, SOCRATES and COMPASS. These models were developed for Fletcher Challenge and Norske Skög, and are published in Philpott and Everett (2001), Everett *et al.* (2000) and Everett *et al.* (2001). PIVOT is a tactical planning model which focuses on the allocation of raw material suppliers and customers to mills, and products to paper machines. The successful implementation of PIVOT led to the development of SOCRATES and COMPASS, which are strategic planning models focused on decisions related to upgrading existing paper machines in order to improve product quality or enable the production of new products. Bredström *et al.* (2004) also present a pair of operational planning models developed for Södra Cell. These models focus on the allocation of production plans to mills.

This paper proposes an original strategic planning model focused on the partitioning of fibre supplies into grades, the allocation of fibre grades to process streams, the selection of production technologies and capacities, and the establishment of end-product range compositions. Section 2 of the paper presents an overview of the pulp and paper industry value chain. It also introduces the modeling constructs used, and presents the mathematical details of the model. Section 3 presents the approach used to validate the model, and discusses how the model can be used to support strategic decision making using a realistic test case. Section 4 offers some conclusions and suggestions for future work.

2 Model Formulation

2.1 The pulp and paper industry value chain

Figure 1 presents a general overview of the pulp and paper industry value chain. This chain begins with standing trees in the forest. Most of Canada's forests are natural growth woodlands which are owned by the government. The government grants forest product companies licenses to harvest specific volumes of wood from specific sites according to a tenure system. Natural variations in site conditions, tree species and tree age lead to significant fibre property variations within the Canadian wood supply.

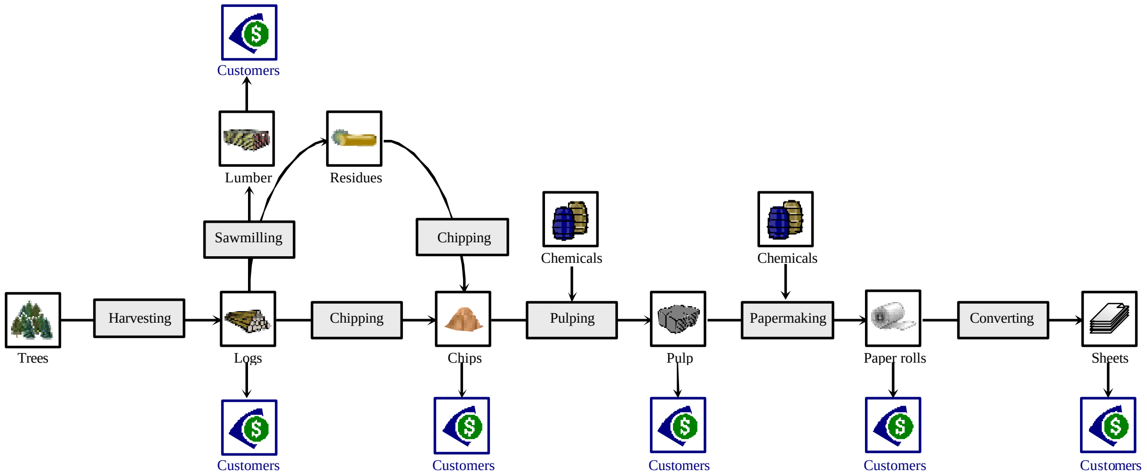

Figure 1: The pulp and paper industry value chain

Most of the wood harvested in Canada is used in lumber production. A smaller proportion is harvested and converted directly into chips. These chips, together with those reclaimed from lumber production residues, are used to produce pulp. The pulp is then used to produce paper, which may either be sold in the form of bulk rolls or converted and sold in the form of sheets or cut-to-size rolls.

2.2 Modeling concepts

The model presented in this paper focuses on the operations of a single integrated pulp and paper mill as shown in *Figure 2*. This mill has access to a set of log and chip grades which are supplied by either *internal supply sources* such as affiliated forestry and sawmilling operations, or *external supply sources* such as independent log and chip vendors. Fibre resources purchased from internal supply sources may be sorted into grades before they are delivered to the mill. Some of these grades may be sold back to the log and chip markets, and others may be used to produce pulp. The pulp may either be sold to the pulp market or used to produce paper. Certain pulp grades not produced by the mill may also be purchased from the pulp market for use in paper production. The paper produced may be sold in the form of rolls, or converted and sold in the form of sheets.

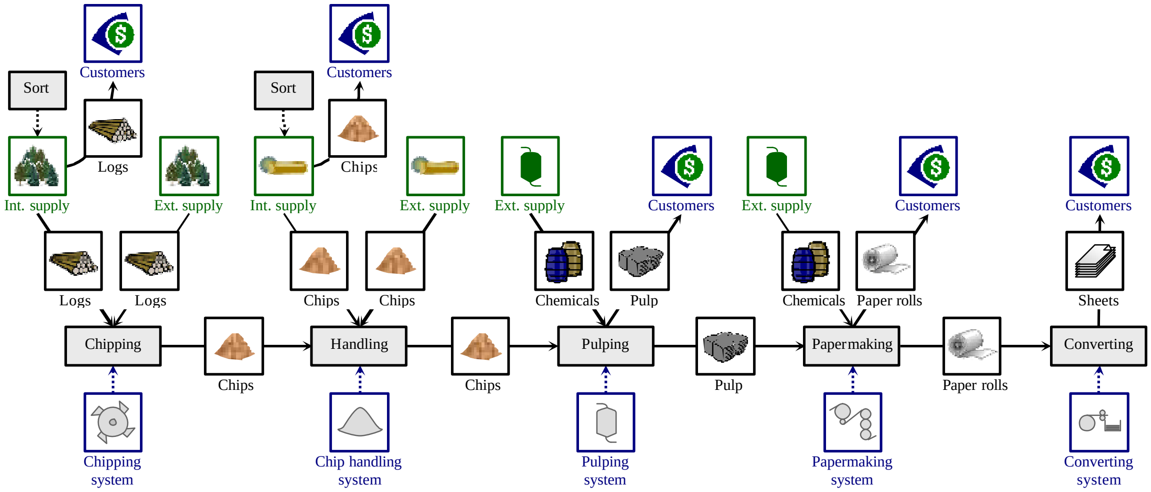

Figure 2: Model elements and material flows

A series of *production recipes* are used to define the transformation of inputs into outputs using various *production systems*. The objective of the model is to maximize the total profit generated within the system under specified fibre supply and market conditions. The model achieves this objective by finding optimal strategies for partitioning fibre supplies into grades, allocating fibre grades to specific processes and end-products, selecting appropriate production technologies and capacities, and establishing end-product range compositions.

The model makes use of a number of key conceptual elements. The use of the terms "*product*", "*product group*", "*supply source*", "*sorting option*", "*production system*", "*production recipe*", "*external paper converter*", and "*customer*" is described below.

The term "*product*" and the index *p* are used to define materials used or produced in the system. These materials include logs, chips, pulp, bulk paper, converted paper, and non-fibre products. Products may be purchased from supply sources, manufactured using various production systems, or sold to customers. The term "*product group*" and the index *g* are used to define sets of products with similar properties which constitute single products for the purposes of sales and marketing. For example, a group of pulps manufactured using slightly different production recipes might be grouped together into a single product group called *Northern bleached softwood kraft pulp*.

The term "*supply source*" and the index *s* are used to define suppliers of products used in pulp and paper production. For log and chip grades, the term "*internal supply source*" is used to define affiliated suppliers with which the mill has some direct relationship, and the term "*external supply source*" is used to define independent suppliers with which the mill has no direct relationship. A single internal log or chip supply source may provide one or several different fibre grades, depending on how the aggregate supply from that source is divided.

The term "*sorting option*" and the index *i* are used to define strategies available for dividing aggregate log and chip supplies into distinct grades. Sorting options only apply to *internal* supply sources, and it is assumed that the mill has some influence over which sorting option is implemented. The procurement cost for each log and chip grade purchased from an internal supply source is assumed to be dependent on the sorting option used. When using the model, a set of viable sorting options is established for each internal log and chip supply source based on the distribution of wood and fibre properties within the aggregate supply, and the mill's ability to use those properties to improve process efficiency or enhance end-product quality. Exclusivity constraints are used to ensure that a single sorting option is implemented at each internal supply source.

The term "*production system*" and the index *m* are used to define groups of technologies used to perform product transformations. Production systems are divided into "*chipping systems*" used to convert logs into chips, "*chip handling systems*" used to store and handle chips at the mill, "*pulp production systems*" used to convert chips into pulp, "*paper production systems*" used to convert pulp into bulk paper rolls, and "*paper conversion systems*" used to convert paper rolls into sheets.

Chipping and paper conversion system requirements are assumed to be functions of the volumes and grades of products produced. It is assumed that different systems may have different operating costs and product recovery efficiencies. The chip handling system requirement is assumed to be a function of the number of different chip grades used in production.

Pulp and paper production system requirements are assumed to be functions of the volumes and grades of products produced. Each pulp and paper production system is comprised of a unique combination of individual or aggregated equipment components which carry the index e. The inclusion or exclusion of different components determines the *type* of products each system is capable of producing, and the capacities of the various components determine the *volume* of products each system is capable of producing. An example based on a mechanical pulp production line is shown in *Figure 3*. In this example, *Component 2* is an aggregate of basic pre-steaming, refining, latency removal, screening, and storage systems. These enable the production of unbleached thermomechanical pulps (TMPs). *Component 1* is a chemical impregnation system which further enables the production of chemithermomechanical pulps (CTMPs), and *Component 3* is a bleaching system which further enables the production of bleached pulps. The capacity of *Component 1* constrains the volume of CTMP produced, the capacity of *Component 3* constrains the volume of bleached pulp produced, and the capacity of *Component 2* constrains the total volume of all pulps produced.

Each production system has its own unique implementation cost. When using the model, a set of viable system options is established based on projected needs. The size of these systems is implicitly constrained by the availability of production space at the mill, and exclusivity constraints are used to ensure that no more than one system of each type is implemented.

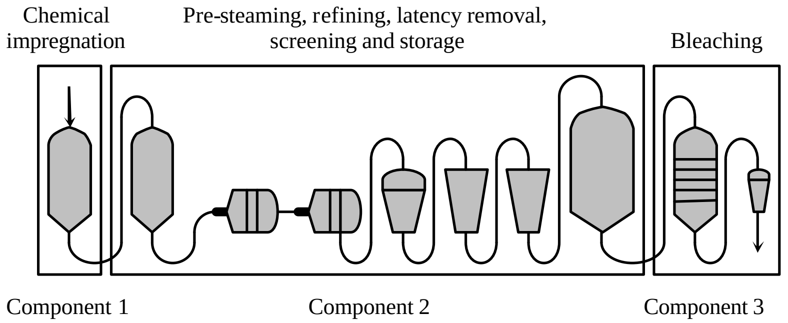

Figure 3: Example of equipment components included in a mechanical pulp production line

The term “*production recipe*” and the index r are used to define the types and quantities of inputs and the production system used to produce a specific grade of pulp or paper. When using the model, a set of viable production recipes is established for each pulp and paper grade based on the properties of the available fibre inputs, and the relationships between those properties and various processing requirements. These recipes are implicitly constrained by the quality requirements of the associated end-product. Each recipe has its own unique fixed and variable production costs.

The term "*external paper converter*" and the index *j* are used to define external providers of paper conversion services. It is assumed that different external paper converters may be capable of handling different product grades, and may have different trim loss factors. Each external paper converter has its own unique fixed and variable production costs.

The term "*customer*" and the index *c* are used to define consumers of products. Customers may constitute individual clients or aggregated demand zones.

2.3 Model formulation

The model uses the following sets and subsets:

P	set of all products ($p \in P$)
PN	subset of non-fibre products ($PN \subset P$)
PA	subset of log grades ($PA \subset P$)
PB	subset of chip grades ($PB \subset P$)
PC	subset of pulp grades ($PC \subset P$)
PD	subset of bulk paper grades ($PD \subset P$)
PE	subset of converted paper grades ($PE \subset P$)
PP	subset of chip and converted paper grades ($PP = PB \cup PE$)
PP_p^{out}	subset of chip and converted paper grades which can be derived from log or bulk paper grade p ($PP_p^{out} \subset PP$)
PX	subset of log and chip grades ($PX = PA \cup PB$)
PY	subset of pulp and paper grades ($PY = PC \cup PD \cup PE$)
PZ	subset of products available from external supply sources ($PZ \subset PN \cup PA \cup PB \cup PC$)
P_g	subset of products included in product group g ($P_g \subset P$)
P_m	subset of chip and converted paper grades which can be produced using chipping or paper conversion system m ($P_m \subset PB \cup PE$)
G	set of all product groups ($g \in G$)
GA	subset of log product groups ($GA \subset G$)

GB	subset of chip product groups ($GB \subset G$)
GC	subset of pulp product groups ($GC \subset G$)
GD	subset of bulk paper product groups ($GD \subset G$)
GE	subset of converted paper product groups ($GE \subset G$)
C	set of all customers ($c \in C$)
C_p	subset of customers of product p ($C_p \subset C$)
C_g	subset of customers of product group g ($C_g \subset C$)
S	set of all supply sources ($s \in S$)
S^{int}	subset of internal supply sources ($S^{int} \subset S$)
S_p^{int}	subset of internal supply sources of product p ($S_p^{int} \subset S^{int}$)
S^{ext}	subset of external supply sources ($S^{ext} \subset S$)
S_p^{ext}	subset of external supply sources of product p ($S_p^{ext} \subset S^{ext}$)
I	set of all sorting options ($i \in I$)
I_s	subset of sorting options available to internal supply source s ($I_s \subset I$)
E	set of all equipment components ($e \in E$)
M	set of all production system options ($m \in M$)
MA	subset of chipping system options ($MA \subset M$)
MB	subset of chip handling system options ($MB \subset M$)
MC	subset of pulp production system options ($MC \subset M$)
MD	subset of paper production system options ($MD \subset M$)
ME	subset of paper conversion system options ($ME \subset M$)
M_r	subset of pulp and paper production system options which enable the use of recipe r ($M_r \subset MC \cup MD$)
M_e	subset of pulp and paper production system options which include equipment component e ($M_e \subset MC \cup MD$)
M_p	subset of chipping and paper conversion system options capable of producing chip or converted paper grade p ($M_p \subset MB \cup ME$)
R	set of all pulp and paper production recipes ($r \in R$)
R_p^{out}	subset of recipes which output pulp or paper product p ($R_p^{out} \subset R$)
R_p^{in}	subset of recipes which use product p as an input ($R_p^{in} \subset R$)
R_e	subset of recipes which use equipment component e ($R_e \subset R$)
J	set of all external paper converters ($j \in J$)

J_p	subset of external paper converters capable of producing converted paper grade p ($J_p \subset J$)

The model also uses the following parameters:

$r_{p,c}$	revenue per unit of product p sold to customer c
$c_{p,s}$	procurement cost per unit of product p purchased from external supply source s
$c_{p,s,i}$	procurement cost per unit of log or chip grade p purchased from internal supply source s when using sorting option i
c_m	fixed cost of implementing production system m
$c_{p,m}^{fix}$	fixed production cost associated with producing chip or converted paper grade p internally using chipping or paper conversion system m
$c_{p,m}^{var}$	variable production cost associated with producing chip or converted paper grade p internally using chipping or paper conversion system m
c_r^{fix}	fixed production cost associated with producing pulp/paper products using recipe r
c_r^{var}	variable production cost associated with producing pulp/paper products using recipe r
$c_{p,j}^{fix}$	fixed production cost associated with producing converted paper grade p at external paper converter j
$c_{p,j}^{var}$	variable production cost associated with producing converted paper grade p at external paper converter j
$c_{p,c}$	transportation cost per unit of pulp/paper grade p delivered to customer c
$c_{p,c,s}$	transportation cost per unit of log or chip grade p delivered to customer c from internal supply source s
$c_{p,c,j}$	transportation cost per unit of converted paper grade p delivered to customer c from external paper converter j
$d_{g,c}$	demand for product group g from customer c
$h_{p,s,i}$	proportion of log or chip grade p contained in the aggregate supply of internal supply source s when using sorting option i
$g_{p,p',m}$	units of log or bulk paper grade p required to produce a single unit of chip or converted paper grade p' using chipping or paper conversion system m
$g_{p,r}$	units of product p required to produce a single unit of pulp/paper product using recipe r
$g_{p,p',j}$	units of bulk paper grade p required to produce a single unit of converted paper grade p' using external paper converter j
$a_{p,m}$	units of capacity required to produce a single unit of chip or converted paper grade p

	using chipping or paper conversion system m
$a_{e,r}$	units of capacity of equipment component e required to produce a single unit of pulp/ paper grade using recipe r
k_m	units of capacity provided by chipping or paper conversion system m
$k_{e,m}$	units of capacity of equipment component e provided by pulp/paper production system m
n_m	maximum number of different chip grades handled by chip handling system m
$\bar{b}_r$	upper limit on the production of pulp or paper products using recipe r
$\bar{b}_p$	upper limit on the internal production of chip or converted paper grade p
$\bar{b}_{p,s}$	upper limit on the purchase of product p from external supply source s
$\underline{b}_{p,s}$	lower limit on the purchase of product p from external supply source s
$\bar{b}_{s,i}$	upper limit on the purchase of log or chip grades from internal supply source s when using sorting option i
$\underline{b}_{s,i}$	lower limit on the purchase of log or chip grades from internal supply source s when using sorting option i
$\bar{b}_j$	upper limit on the production of converted paper grades at external paper converter j
$\underline{b}_j$	lower limit on the production of converted paper grades at external paper converter j

The model also uses the following decision variables:

$F_{p,c}$	units of pulp/paper product p sold to customer c
$F_{p,c,s}$	units of log or chip grade p sold to customer c from internal supply source s
$F_{p,c,j}$	units of converted paper grade p sold to customer c from external paper converter j
$F_{p,s}$	units of product p purchased from external supply source s
$F_{s,i}$	units of log/chip grades purchased from internal supply source s when using sorting option i
$X_{p,m}$	units of chip or converted paper grade p produced internally using chipping or paper conversion system m
X_r	units of pulp/paper product produced using recipe r
$X_{p,j}$	units of converted paper grade p produced at external paper converter j
$Y_{s,i}^{srt}$	binary variable with value 1 if sorting option i is used at internal supply source s and value 0 otherwise
Y_m^{sys}	binary variable with value 1 if production system m is used and value 0 otherwise
Y_r^{rec}	binary variable with value 1 if recipe r is used and value 0 otherwise

Y_p^{chip}	binary variable with value 1 if chip grade p is used in production and value 0 otherwise
$Y_{p,m}^{int}$	binary variable with value 1 if chip or converted paper grade p is produced internally using chipping or paper conversion system m and value 0 otherwise
Y_j^{ext}	binary variable with value 1 if external paper converter j is used and value 0 otherwise
$Y_{p,j}^{ext}$	binary variable with value 1 if converted paper grade p is produced at external paper converter j is used and value 0 otherwise

Solving the following mixed integer programming model maximizes the value created by the pulp and paper mill.

$$\text{Maximize } \sum_{p\in PX}\sum_{c\in C_p}\sum_{s\in S_p^{\text{int}}} r_{p,c}F_{p,c,s} + \sum_{p\in PY}\sum_{c\in C_p} r_{p,c}F_{p,c} + \sum_{p\in PE}\sum_{c\in C_p}\sum_{j\in J_p} r_{p,c}F_{p,c,j} -$$

(Sales revenues)

$$c^{fix} - \sum_{m\in M} c_m Y_m^{sys} - \sum_{p\in PP}\sum_{m\in M_p} c_{p,m}^{fix} Y_{p,m}^{int} - \sum_{r\in R} c_r^{fix} Y_r^{rec} - \sum_{p\in PE}\sum_{j\in J_p} c_{p,j}^{fix} Y_{p,j}^{ext} -$$

(Fixed overhead, equipment implementation, and production costs)

$$\sum_{p\in PX}\sum_{s\in S_p^{int}}\sum_{i\in I_s} c_{p,s,i} h_{p,s,i} F_{s,i} - \sum_{p\in PZ}\sum_{s\in S_p^{ext}} c_{p,s}F_{p,s} - \sum_{p\in PP}\sum_{m\in M_p} c_{p,m}^{var} X_{p,m} - \sum_{r\in R} c_r^{var} X_r - \sum_{p\in PE}\sum_{j\in J_p} c_{p,j}^{var} X_{p,j} -$$

(Variable material procurement and production costs)

$$\sum_{p\in PX}\sum_{c\in C_p}\sum_{s\in S_p^{int}} c_{p,c,s}F_{p,c,s} - \sum_{p\in PY}\sum_{c\in C_p} c_{p,c}F_{p,c} - \sum_{p\in PE}\sum_{c\in C_p}\sum_{j\in J_p} c_{p,c,j}F_{p,c,j}$$

(Variable transportation costs)

subject to

Market opportunity constraints for log and chip product groups:

$$\sum_{p\in P_g}\sum_{s\in S_p^{int}} F_{p,c,s} \le d_{g,c} \qquad \forall g\in GA\cup GB \quad \forall c\in C_g \qquad (1)$$

Market opportunity constraints for pulp and bulk paper product groups:

$$\sum_{p\in P_g} F_{p,c} \le d_{g,c} \qquad \forall g\in GC\cup GD \quad \forall c\in C_g \qquad (2)$$

Market opportunity constraints for converted paper product groups:

$$\sum_{p\in P_g} F_{p,c} + \sum_{p\in P_g}\sum_{j\in J_p} F_{p,c,j} \le d_{g,c} \qquad \forall g\in GE \quad \forall c\in C_g \qquad (3)$$

Flow conservation constraints for non-fibre product grades:

$$\sum_{s\in S_p^{ext}} F_{p,s} = \sum_{r\in R_p^{in}} g_{p,r} X_r \qquad \forall p\in PN \qquad (4)$$

Flow conservation constraints for log grades:

$$\sum_{s\in S_p^{int}}\sum_{i\in I_s} h_{p,s,i}F_{s,i} + \sum_{s\in S_p^{ext}} F_{p,s} = \sum_{c\in C_p}\sum_{s\in S_p^{int}} F_{p,c,s} + \sum_{p'\in PP_p^{out}}\sum_{m\in M_{p'}} g_{p,p',m}X_{p',m} \qquad \forall p\in PA \tag{5}$$

Flow conservation constraints for chip grades:

$$\sum_{s\in S_p^{int}}\sum_{i\in I_s} h_{p,s,i}F_{s,i} + \sum_{s\in S_p^{ext}} F_{p,s} + \sum_{m\in MA} X_{p,m} = \sum_{c\in C_p}\sum_{s\in S_p^{int}} F_{p,c,s} + \sum_{r\in R_p^{in}} g_{p,r}X_r \qquad \forall p\in PB \tag{6}$$

Flow conservation constraints for pulp grades:

$$\sum_{s\in S_p^{ext}} F_{p,s} + \sum_{r\in R_p^{out}} X_r = \sum_{c\in C_p} F_{p,c} + \sum_{r\in R_p^{in}} g_{p,r}X_r \qquad \forall p\in PC \tag{7}$$

Flow conservation constraints for bulk paper grades:

$$\sum_{r\in R_p^{out}} X_r = \sum_{c\in C_p} F_{p,c} + \sum_{p'\in PP_p^{out}}\sum_{m\in M_{p'}} g_{p,p',m}X_{p',m} + \sum_{p'\in PP_p^{out}}\sum_{j\in J_{p'}} g_{p,p',j}X_{p',j} \qquad \forall p\in PD \tag{8}$$

Flow conservation constraints for converted paper grades produced internally:

$$\sum_{m\in M_p} X_{p,m} = \sum_{c\in C_p} F_{p,c} \qquad \forall p\in PE \tag{9}$$

Flow conservation constraints for converted paper grades produced externally:

$$X_{p,j} = \sum_{c\in C_p} F_{p,c,j} \qquad \forall p\in PE \quad \forall j\in J_p \tag{10}$$

Sales constraints for log and chip grades:

$$\sum_{c\in C_p} F_{p,c,s} \le \sum_{i\in I_s} h_{p,s,i}F_{s,i} \qquad \forall p\in PX \quad \forall s\in S_p^{int} \tag{11}$$

Procurement constraints for external supply sources:

$$\underline{b}_{p,s} \le F_{p,s} \le \bar{b}_{p,s} \qquad \forall p\in PZ \quad \forall s\in S_p^{ext} \tag{12}$$

Procurement constraints for internal supply sources:

$$\underline{b}_{s,i}Y_{s,i}^{srt} \le F_{s,i} \le \bar{b}_{s,i}Y_{s,i}^{srt} \qquad \forall s\in S^{int} \quad \forall i\in I_s \tag{13}$$

First pulp and paper production constraints:

$$Y_r^{rec} \le Y_m^{sys} \qquad \forall r\in R \quad \forall m\in M_r \tag{14}$$

Second pulp and paper production constraints:

$$X_r \le \bar{b}_r Y_r^{rec} \qquad \forall r\in R \tag{15}$$

First internal chip production and paper conversion constraints:

$$Y_{p,m}^{int} \le Y_m^{sys} \qquad \forall p \in PP \quad \forall m \in M_p \tag{16}$$

Second internal chip production and paper conversion constraints:

$$X_{p,m} \le \bar{b}_p Y_{p,m}^{int} \qquad \forall p \in PP \quad \forall m \in M_p \tag{17}$$

First external paper conversion constraints:

$$Y_{p,j}^{ext} \le Y_j^{ext} \qquad \forall p \in PE \quad \forall j \in J_p \tag{18}$$

Second external paper conversion constraints:

$$X_{p,j} \le \bar{b}_j Y_{p,j}^{ext} \qquad \forall p \in PE \quad \forall j \in J_p \tag{19}$$

Pulp and paper production system capacity constraints:

$$\sum_{r \in R_e} a_{e,r} X_r \le \sum_{m \in M_e} k_{e,m} Y_m^{sys} \qquad \forall e \in E \tag{20}$$

Chipping and paper conversion system capacity constraints:

$$\sum_{p \in P_m} a_{p,m} X_{p,m} \le k_m Y_m^{sys} \qquad \forall m \in MA \cup ME \tag{21}$$

External paper converter capacity constraints:

$$\underline{b}_j Y_j^{ext} \le \sum_{p \in PE} X_{p,j} \le \bar{b}_j Y_j^{ext} \qquad \forall j \in J \tag{22}$$

First chip handling system selection constraints:

$$Y_p^{chip} \le \sum_{r \in R_p^{in}} Y_r^{rec} \qquad \forall p \in PB \tag{23}$$

Second chip handling system selection constraints:

$$\sum_{r \in R_p^{in}} g_{p,r} X_r \le \left[\sum_{r \in R_p^{in}} \bar{b}_r \right] Y_p^{chip} \qquad \forall p \in PB \tag{24}$$

Third chip handling system selection constraints:

$$\sum_{p \in PB} Y_p^{chip} = \sum_{m \in MB} n_m Y_m^{sys} \tag{25}$$

Production system exclusivity constraints:

$$\sum_{m \in MA} Y_m^{sys} \le 1 \;, \quad \sum_{m \in MB} Y_m^{sys} \le 1 \;, \quad \sum_{m \in MC} Y_m^{sys} \le 1 \;, \quad \sum_{m \in MD} Y_m^{sys} \le 1 \;, \quad \sum_{m \in ME} Y_m^{sys} \le 1 \tag{26}$$

Sorting option exclusivity constraints:

$$\sum_{i \in I_s} Y_{s,i} = 1 \qquad \forall s \in S^{int} \tag{27}$$

Non-negativity constraints:

$$F_{p,c} \geq 0 \qquad \forall p \in PY \quad \forall c \in C_p \tag{28}$$

$$F_{p,c,s} \geq 0 \qquad \forall p \in PX \quad \forall c \in C_p \quad \forall s \in S_p^{int} \tag{29}$$

$$F_{p,c,j} \geq 0 \qquad \forall p \in PE \quad \forall c \in C_p \quad \forall j \in J_p \tag{30}$$

$$F_{p,s} \geq 0 \qquad \forall p \in PZ \quad \forall s \in S_p^{ext} \tag{31}$$

$$F_{s,i} \geq 0 \qquad \forall s \in S^{int} \quad \forall i \in I_s \tag{32}$$

$$X_{p,m} \geq 0 \qquad \forall p \in PP \quad \forall m \in M_p \tag{33}$$

$$X_r \geq 0 \qquad \forall r \in R \tag{34}$$

$$X_{p,j} \geq 0 \qquad \forall p \in PE \quad \forall j \in J_p \tag{35}$$

$$Y_{s,i}^{srt} \in \{1,0\} \qquad \forall s \in S^{int} \quad \forall i \in I_s \tag{36}$$

$$Y_m^{sys} \in \{1,0\} \qquad \forall m \in M \tag{37}$$

$$Y_r^{rec} \in \{1,0\} \qquad \forall r \in R \tag{38}$$

$$Y_p^{chip} \in \{1,0\} \qquad \forall p \in PB \tag{39}$$

$$Y_{p,m}^{int} \in \{1,0\} \qquad \forall p \in PP \quad \forall m \in M_p \tag{40}$$

$$Y_j^{ext} \in \{1,0\} \qquad \forall j \in J \tag{41}$$

$$Y_{p,j}^{ext} \in \{1,0\} \qquad \forall p \in PE \quad \forall j \in J_p \tag{42}$$

The model's objective function is expressed as a maximization of sales revenues minus various fixed and variable costs. Sales revenues are divided into three terms corresponding to the sale of logs and chips from internal supply sources, the sale of pulp and paper products from the mill, and the sale of converted paper products from external paper converters. The unit sales revenue for each product-customer pair is assumed to be independent of volume.

Fixed costs are divided into overhead costs, equipment implementation costs, and fixed production costs. The overhead cost term includes all infrastructure costs not directly associated with production. The equipment implementation cost term includes the costs of decommissioning, reconfiguring or installing production systems. It also includes the costs of amortizing equipment purchases and the opportunity costs associated with invested capital. Fixed production costs are divided into three terms corresponding to the production of chips and converted paper products at the mill, the production of pulp and bulk paper products at the mill, the production of converted paper products at external paper converters. These terms assume that a fixed setup cost is incurred for each product produced and each recipe used during the planning period.

Variable costs are divided into material procurement costs, variable production costs, and transportation costs. Material procurement costs are divided into two terms corresponding to the procurement of logs and chips from internal supply sources, and the procurement of logs, chips, pulps and chemicals from external supply sources. Variable production costs are divided into three terms corresponding to the production of chips and converted paper products at the mill, the production of pulp and bulk paper products at the mill, and the production of converted paper products at external paper converters. Transportation costs are divided into three terms corresponding to the transport of logs and chips from internal supply sources to customers, the transport of pulp and paper products from the mill to customers, and the transport of converted paper products from external paper converters to customers. All unit procurement, production, and transportation costs are assumed to be independent of volume.

Constraints (1) through (3) ensure that sales to customers do not exceed customer demand. These constraints are expressed as less than or equal to relationships because the objective of the model is to determine which demands are most profitable to fulfill. When contractual obligations exist, some of these constraints may be changed to equalities. Constraint (1) assumes that only log and chip grades originating from internal supply sources may be sold to customers.

Constraints (4) through (10) ensure flow conservation for each product subset. Constraints (4) through (8) use the parameter $g_{p,r}$ together with the subset R_p^{in}, and the parameters $g_{p,p',m}$ and $g_{p,p',j}$ together with the subset PP_p^{out}, to define quantities of products used in downstream processes. Constraints (5) and (6) use the parameter-variable pair $h_{p,s,i}F_{s,i}$ to link the amount of each log and chip grade available from an internal supply source to its proportion in the aggregate supply and the sorting option selected.

Constraint (11) ensures that sales of log and chip grades do not exceed the amounts available from internal supply sources. Constraints (12) and (13) ensure that purchases of all products from all supply sources fall between the upper and lower limits established for those purchases. Constraint (13) uses the binary variable $Y_{s,i}$ to restrict the value of the procurement variable $F_{s,i}$ to 0 if sorting option i is not implemented at supply source s.

Constraints (14) and (15) set the values of the recipe use variable Y_r^{rec} and perform the selection of the pulp and paper production systems. Constraint (14) uses the binary variable Y_m^{sys} together with the subset M_r to restrict the value of Y_r^{rec} to 0 if recipe r is not supported by production system m. Constraint (15) uses the production variable X_r to force the value of Y_r^{rec} to 1 if any amount of product is produced using recipe r. Constraints (16) and (17) use similar logic to set the values of the internal chip production and paper conversion variable $Y_{p,m}^{int}$ using the variables Y_m^{sys} and $X_{p,m}$ and the subset M_p. Constraints (18) and (19) use similar logic to set the values of the external paper conversion variable $Y_{p,j}^{ext}$ using the variables Y_j^{ext} and $X_{p,j}$ and the subset J_p.

Constraints (20) and (21) ensure that production does not exceed the capacity of the production systems selected. Constraint (20) uses the parameter-variable pair $k_{e,m}Y_m^{sys}$ to define the number of units of capacity of equipment component e available during the planning period, and the parameter-variable pair $a_{e,r}X_r$ to define the number of units of that capacity required during the planning period. Constraint (21) uses similar logic with the pairs $k_mY_m^{sys}$ and $a_{p,m}X_{p,m}$.

Constraint (22) ensures that external paper conversion does no exceed the capacity of the external paper converters used. This constraint uses the binary variable Y_j^{ext} to restrict the value of the paper conversion variable $X_{p,j}$ to 0 if external paper converter j is not used.

Constraints (23) through (25) perform the selection of a chip handling system based on the number of different chip grades used at the mill. Constraint (23) uses the binary variable Y_r^{rec} and the subset R_p^{in} to restrict the value of the chip use variable Y_p^{chip} to 0 if chip grade p is not used in production. Constraint (24) uses the parameter-variable pair $g_{p,r}X_r$ to force the value of Y_p^{chip} to 1 if any amount of chip grade p is used in production. Constraint (25) then forces the value of the system selection variable Y_m^{sys} to 1 when m is equal to the number of chip grades used.

Constraint (26) ensures that no more than one chipping, chip handling, pulp production, paper production, and paper conversion system are selected. These constraints are expressed as a less than or equal to relationships because the objective of the model is to determine which processes are the most profitable to maintain. Constraint (27) ensures that a single sorting option is selected for each internal log and chip supply source. Constraints (28) through (42) are binary and sign restrictions.

3 Model Validation

3.1 Validation approach

Validating the model and demonstrating its utility involved three steps: the development of a prototype decision support tool, the elaboration of a test case based on a realistic integrated pulp and paper mill, and the analysis of a set of test scenarios. This approach was used to show that the model can be solved, that the solutions obtained are reasonable, and that using the model can provide substantial value.

The prototype was implemented using ILOG OPL Studio 4.0 with ILOG CPLEX 9.1 as solver. Optimizations were performed on a PC running Microsoft Windows XP and equipped with a 2 GHz Intel Pentium M processor and 2 GB of RAM. The test case and scenario analyses are described in detail below. The test scenarios generated approximately 270 continuous variables, 130 binary variables and 550 constraints; these were solved by CPLEX in approximately 2 seconds. Real problems are likely to be significantly larger than the test scenarios, but probably not so much larger that they will require complex solution heuristics.

3.2 Test case

The test case was based on the typical integrated pulp and paper mill shown in *Figure 4*. It is assumed that this mill already has all necessary production systems in place, and that investments in new production systems are not being considered.

The mill has access to a number of internal log supply sources which can provide up to three different hardwood log grades. *Grade 1* is a high density, high fibre coarseness grade similar to high density aspen, and *Grade 2* is a lower density, lower fibre coarseness grade similar to low density aspen. *Grade 3* is an equal-parts mixture of grades 1 and 2. The pulp and paper properties associated with these grades were based on data published by Hunt *et al.* (1999) and Gullichsen *et al.* (1999). Two sorting options are available for each log supply source. *Sort 1* involves using the aggregate supply without any sorting, which yields log grade 3. *Sort 2* involves separating the supply into two distinct grades, which yields log grades 1 and 2.

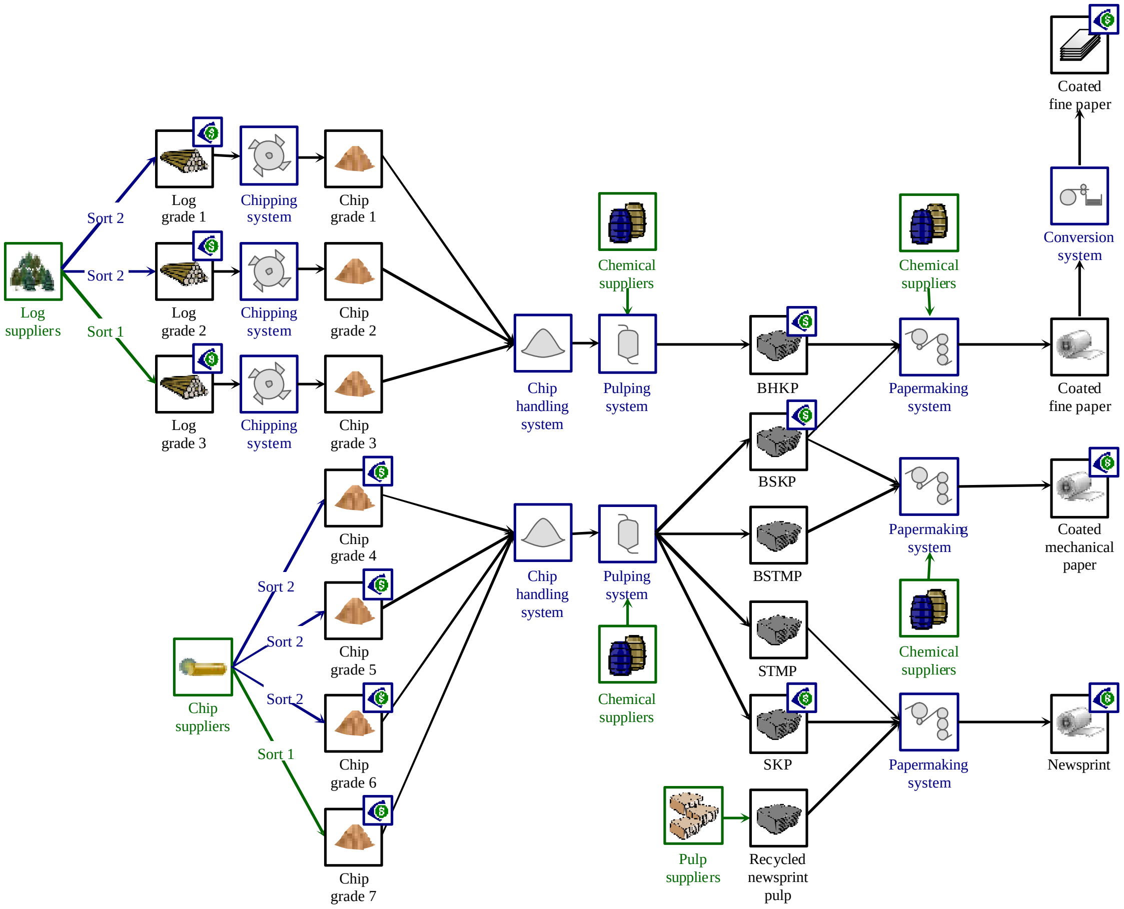

Figure 4: Structure of the integrated pulp and paper mill used to test the model.

The mill also has access to a number of internal chip supply sources which can provide up to four different softwood chip grades. *Grade 4* is a low density, low fibre coarseness grade similar to western SPF (a mixture of white spruce, lodgepole pine and subalpine fir), *Grade 5* is a high density, high fibre coarseness grade similar to Douglas fir, and *Grade 6* is an intermediate grade similar to hembal (a mixture of western hemlock and amabilis fir). *Grade 7* is an equal-parts mixture of grades 4, 5 and 6. The pulp and paper properties associated with these grades were based on data published by Hussein *et al.* (2004a, 20004b), Johal *et al.* (2004a, 20004b), Gullichsen *et al.* (1999) and Sundholm (1999).

Two sorting options are available for each chip supply source. *Sort 1* involves using the aggregate supply without any sorting, which yields chip grade 7. *Sort 2* involves separating the supply into three distinct grades, which yields chip grades 4, 5 and 6.

The mill is capable of producing up to five different pulp grades: an unbleached softwood thermomechanical pulp (STMP), a bleached softwood thermomechanical pulp (BSTMP), an unbleached softwood kraft pulp (SKP), a bleached softwood kraft pulp (BSKP), and a bleached hardwood kraft pulp (BHKP). Several different production recipes are available for each of these pulps, depending on the specific chip grades used as inputs. It is assumed that all of the kraft pulps may be sold on the pulp market, but that the thermomechanical pulps must be used in paper production. A recycled newsprint pulp is also available for purchase from external pulp supply sources.

The mill is also capable of producing up to three different paper grades: a standard newsprint made of STMP, SKP and recycled newsprint pulp, a coated mechanical paper made of BSTMP, BSKP and a calcium carbonate coating, and a coated fine paper made of BSKP, BHKP, and a calcium carbonate coating. Several different production recipes are available for each of these papers, depending on the specific pulp grades used as inputs. The newsprint and coated mechanical paper grades are sold in the form of rolls, and the coated fine paper grade is converted and sold in the form of sheets. It is assumed that the mill performs all paper conversion internally.

Unit sales revenues and procurement costs were based on 2003 market price data published by *Paperloop* (DeKing, 2004). Procurement costs for sorted log and chip grades were assumed to be 10% higher those for unsorted grades. This assumption is consistent with what might be expected for a typical Canadian fibre supply. Transportation and production costs were based on data provided by *Fisher International*[1]. These costs were reported as semi-variable, and it was not possible to separate the fixed and variable components. All costs were therefore assumed to be variable, and fixed costs were not included in the analysis.

The energy components of TMP production costs were adjusted for each input chip grade according to the energy consumption data published by Johal *et al.* (2004a, 2004b). Inefficiencies and product losses associated with fibre quality and pulp brightness variations were assumed to increase refining energy demand and production costs by 1% for TMP recipes containing chip grade 7. Similar inefficiencies were assumed to increase production costs by 1% for kraft pulp

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[3] Fisher International. http://www.fisheri.com.

recipes containing chip grades 3 and 7, and by 0.5% for paper recipes containing pulps made from chip grades 3 and 7. These assumptions are conservative estimate of the effects of wood and fibre quality variations on processing costs.

Production recipe parameters for TMP grades were established by assuming a pulp yield of 98% for all chip grades and using the bleaching yield and chemical demand data published by Sundholm (1999). Inefficiencies associated with variations in pulp brightness were assumed to decrease bleaching yield by 0.5% and increase chemical demand by 1% for bleached TMP recipes containing chip grade 7. Production recipe parameters for kraft pulps were established using the pulp yield and chemical demand data published by Hussein *et al.* (2004a, 2004b) and Hunt *et al.* (1999), and the bleaching yield and chemical demand data published by Gullichsen *et al.* (1999). Inefficiencies associated with variations in wood chemistry were assumed to decrease pulp yield by 0.5% and increase chemical demand by 1% for kraft pulp recipes containing chip grades 3 and 7. These inefficiencies were assumed to have no effect on kraft pulp bleaching yield or chemical demand.

Production recipe parameters for the newsprint paper grade were established using a simple linear program to find the least-cost pulp blends satisfying a minimum tensile index constraint. The tensile indexes of the STMP and SKP were based on data published by Hussein *et al.* (2004a, 2004b) and Johal *et al.* (2004a, 2004b), and the tensile index of the recycled newsprint pulp was assumed to be 28N*m/g. The tensile index of the paper was assumed to be a linear combination of the tensile indexes of each pulp in the blend, and the proportion of each pulp in the least-cost blend was then found by solving the linear program:

Minimize $\{\$85(P_x)+c_y(P_y)+c_z(P_z) \mid P_x+P_y+P_z = 1;\ T_xP_x+T_yP_y+T_zP_z = 40;\ P_x = 25\%;\ P_x, P_y, P_z = 0\}$

where P_x, P_y and P_z define the proportions of recycled newsprint, STMP and SKP in the blend, c_y and c_z define STMP and SKP production costs, and T_x, T_y and T_z define the corresponding tensile indexes.

This analysis is included in order to illustrate how furnish optimization fits into the broader context of the model. It should be noted that tensile index is not the only quality consideration important to newsprint, and that paper properties are not always linear combinations of the properties of each pulp in the furnish. A similar approach could have been used to establish production recipe parameters for the coated mechanical and fine paper grades, but for this test case the coated mechanical paper was assumed to contain a constant furnish of 55% BSTMP, 25% BSKP and 20% calcium carbonate, and the coated fine paper was assumed to contain a constant furnish of 55% BSKP, 25% BHKP and 20% calcium carbonate.

Pulp production capacity requirements were assumed to be dependent on chip packing density and yield. Chip packing densities and yields were established based on data published by Hussein *et al.* (2004a, 2004b), Hunt *et al.* (1999), Gullichsen *et al.* (1999) and Sundholm (1999). For mechanical pulping components, a chip grade with a packing density of 200kg/m^3 and a pulp yield of 98% was assumed to use one tonne of capacity per tonne of output. For kraft pulping components, a chip grade with a packing density of 200kg/m^3 and a pulp yield of 50% was assumed to use one tonne of capacity per tonne of output. For bleaching components, a pulp grade with a yield of 97% was assumed to use one tonne of capacity per tonne of output. Inefficiencies and product losses associated with fibre quality variations were assumed to increase capacity requirements by 0.5% for pulp recipes containing the chip grades 3 and 7, and by 0.25% for paper recipes containing pulps made from chip grades 3 and 7.

3.3 Scenario analysis

Three scenarios were elaborated to validate the model and demonstrate its utility. All of these scenarios assume that the system is supply constrained (i.e., the supply of fibre is not sufficient to fulfill all product demand, and production system capacities are high enough that they do not impose binding constraints). *Scenario 1* further assumes that the mill has access to only aggregate log and chip grades (log grade 3 and chip grade 7), and requires the mill to sell equal amounts of each of its marketable products. These constraints are not necessarily realistic, but they establish a basis of comparison for scenarios 2 and 3 and allow us to highlight the significant differences between optimal and sub-optimal production schemes.

In order to implement *Scenario 1*, a total of 1,000,000 m^3 of logs and 1,000,000 tonnes of chips were made available to the mill through internal supply sources. Production capacity and product demand parameters were set high enough so that they did not constrain the system.

Access to the sorted log and chip grades (log grades 1 and 2, and chip grades 4, 5 and 6) was restricted through the addition of the constraints:

$$Y_{s,i}^{srt} = 1 \qquad \forall s \in S^{int} \quad \forall i \in I_s^1 \tag{43}$$

$$Y_{s,i}^{srt} = 0 \qquad \forall s \in S^{int} \quad \forall i \in I_s^2 \tag{44}$$

where I_s^1 is the set of sorting options which involve using the fibre supply from supply source *s* as aggregate (*Sort 1*), and I_s^2 is the set of sorting options which involve dividing the fibre supply from supply source *s* into distinct grades (*Sort 2*).

Sales of all marketable pulp and paper products were forced to a common value through the addition of the constraints:

$$\sum_{p \in P_g} \sum_{c \in C_p} F_{p,c} = F^{com} \qquad \forall g \in GC \cup GD \tag{45}$$

$$\sum_{p \in P_g} \sum_{c \in C_p} F_{p,c} + \sum_{p \in P_g} \sum_{c \in C_p} \sum_{j \in J_p} F_{p,c,j} = F^{com} \qquad \forall g \in GE \tag{46}$$

where F^{com} is the common sales volume of each product.

The maximized objective function value for this scenario was $178,062,213. The optimal production scheme is shown in *Figure 5*. This scheme uses only the aggregate log and chip grades, and produces and sells a constant volume (126,808 tonnes) of each marketable product. The scheme does not use all of the available hardwood log supply because the production volumes of the hardwood-containing products do not require it.

Scenario 2 is similar to *Scenario 1*, but constraints (45) and (46) are removed and the mill is no longer required to sell equal amounts of each of its marketable products. This allows an optimization of end-product range composition.

The maximized objective function value for this scenario was $313,423,721, which represents a 76% increase over the value for *Scenario 1*. This large increase highlights the fact that constraints (45) and (46) are not necessarily realistic. The optimal production scheme is shown in *Figure 6*. This scheme uses only the aggregate log and chip grades, and produces and sells only the higher-margin coated fine and coated mechanical paper grades. The scheme uses all of the available hardwood log supply and most of the available softwood chip supply in the production of coated fine paper. The remainder of the softwood chip supply is used in the production of coated mechanical paper. Neither the coated fine nor the coated mechanical paper grade contains unbleached pulp, and therefore the SKP and STMP grades are not produced.

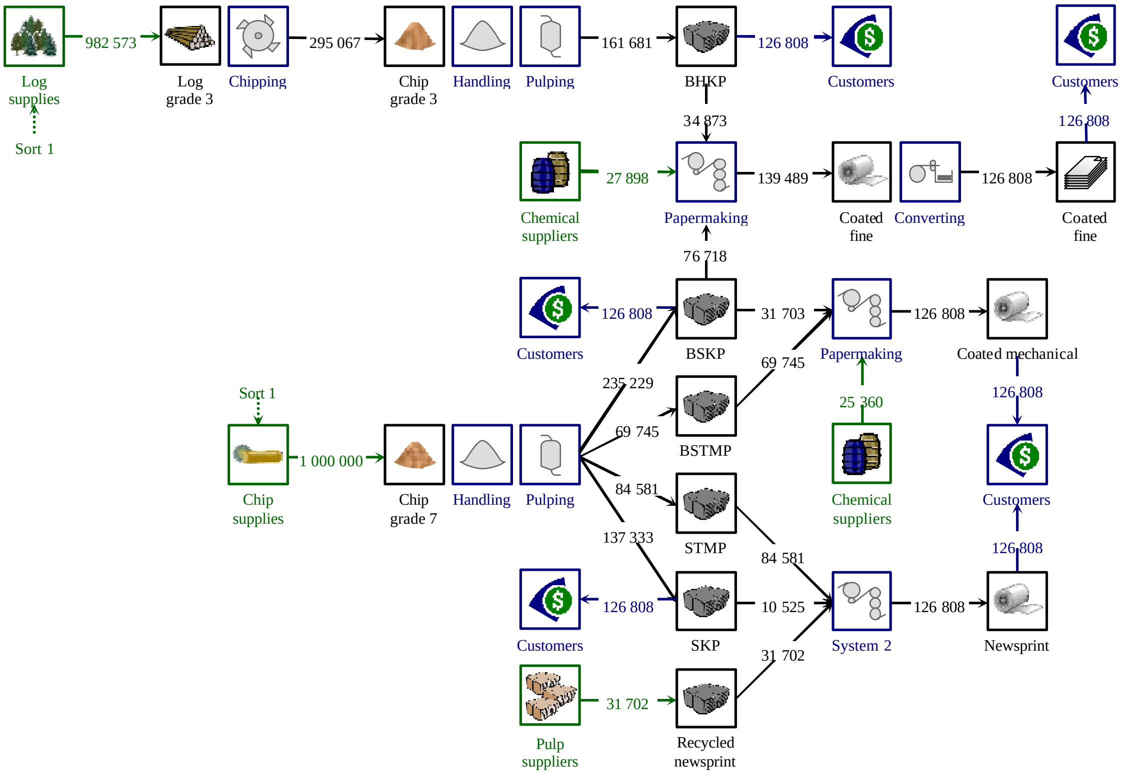

Figure 5: Optimal production scheme for scenario 1

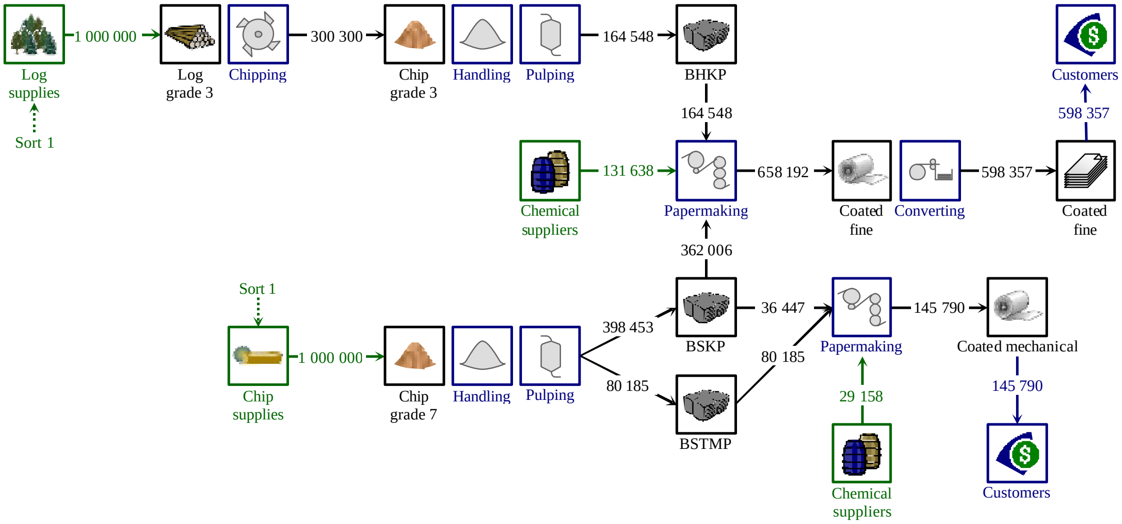

Figure 6: Optimal production scheme for scenario 2

Scenario 3 is similar to scenario 2, but constraints (43) and (44) are removed and the mill is given access to the sorted log and chip grades. This allows an optimization of fibre allocation strategies. The maximized objective function value for this scenario was $321,706,676, which represents a

3% increase over the value for *Scenario 2*. The optimal production scheme is shown in *Figure 7*. This scheme uses only the sorted log and chip grades, and produces and sells only the coated fine and newsprint paper grades. As in *Scenario 2*, the scheme uses all of the available hardwood log supply and most of the available softwood chip supply in the production of coated fine paper. The remainder of the softwood chip supply is used in the production of newsprint. Neither the coated fine nor the newsprint paper grade contains BSTMP, and therefore this pulp grade is not produced.

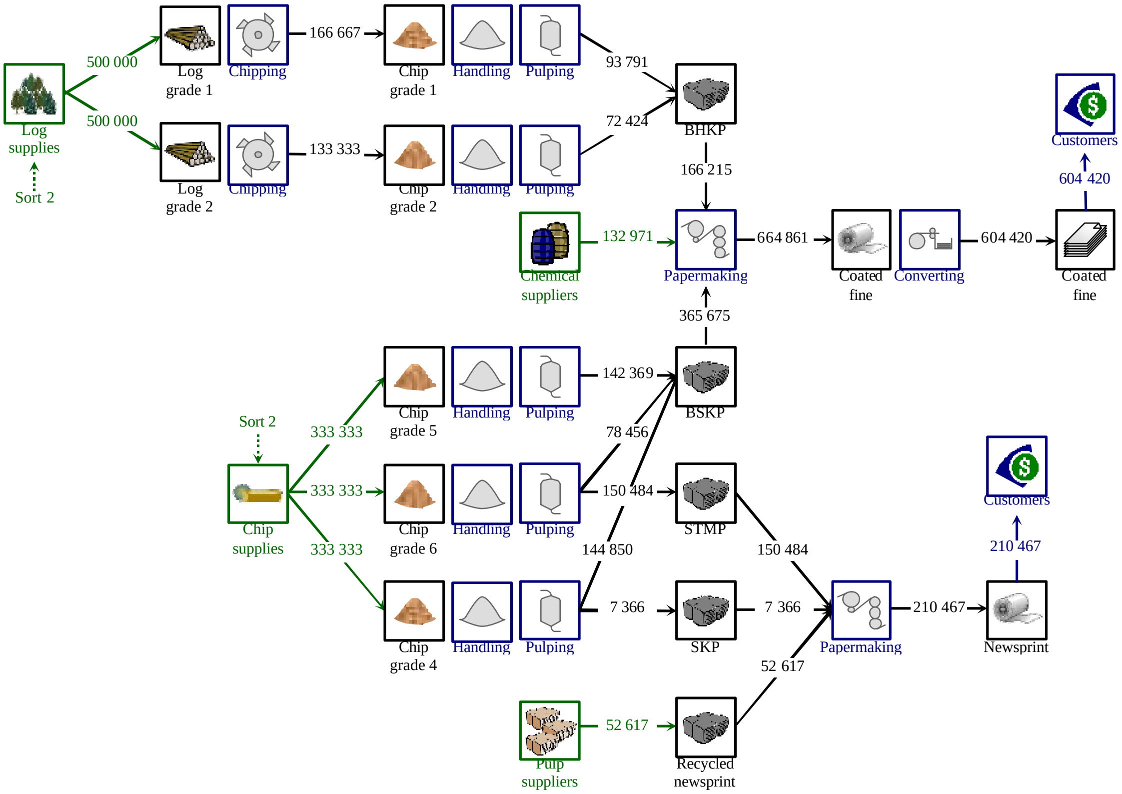

Figure 7: Optimal production scheme for scenario 3

The optimal production scheme uses the highest yield, highest tensile strength softwood chip grade (*Grade 4*) exclusively in the production of kraft pulps, and the lowest refining energy grade (*Grade 6*) to produce all of the thermomechanical pulp required for newsprint production. The reduction in STMP processing costs and the improvement in SKP tensile strength associated with this allocation strategy are likely responsible for making newsprint production more profitable than coated mechanical paper production. The intermediate chip grade (*Grade 5*) is used exclusively in the production of bleached kraft pulp for use in the production of coated fine paper. The strength properties of this pulp are somewhat less important because coated fine paper strength requirements were not included in the production recipe parameters.

4 Concluding Remarks

The model presented above provides a means of addressing the challenge of maximizing the value created form available fibre supplies. It does this by finding optimal strategies for partitioning fibre supplies into grades, allocating fibre grades to specific processes and end-products, selecting appropriate production technologies and capacities, and establishing end-product range compositions.

This model provides, for the first time, a means of including the effects of wood and fibre properties on processing requirements and end-product quality in a strategic-level value chain optimization. It does this by linking sorting strategies, production recipes, and capacity usages to distinct fibre types. The model also provides a means of linking production technology selection to the properties of the fibre supply and the existing market conditions.

The test scenarios presented above illustrate that value creation (or profit generation) can be significantly improved by optimizing the allocation of fibre types to process streams, and the composition of the end-product range. *Scenario 3* illustrates that optimizing both of these at the same time offers the greatest potential for improvement.

The model has been left as flexible as possible, and can be easily adapted to a wide range of industrial scenarios. Future work in this area will include implementing the model in specific industrial settings, and developing a more detailed "*virtual mill*" simulation platform.

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