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**Yan Feng**
**Sophie D'Amours**
**Robert Beauregard**

**December 2007**

**CIRRELT-2007-57**

**Bureaux de Montréal :**
Université de Montréal
C.P. 6128, succ. Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

**Bureaux de Québec :**
Université Laval
Pavillon Palasis-Prince, local 2642
Québec (Québec)
Canada G1K 7P4
Téléphone : 418 656-2073
Télécopie : 418 656-2624

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# The Value of Sales and Operations Planning in Oriented Strand Board Industry with Make-to-Order Manufacturing System: Cross Functional Integration under Deterministic Demand and Spot Market Recourse

**Yan Feng[1,*], Sophie D'Amours[1], Robert Beauregard[1]**

[1] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT), and FORAC Research Consortium, Pavillon Adrien-Pouliot, Université Laval, Québec, Canada G1K 7P4

**Abstract.** Sales and Operations Planning (S&OP) has become a widely recognized process of supply chain planning. However, until the present time, the evaluation of its benefits has been conducted mainly through post implementation case studies. This paper explores the fundamentals of the S&OP process and presents a modeling approach to evaluate its impact before implementation. A mixed integer programming based model is proposed to represent the cross functional integration of the supply chain's sales-production-distribution-procurement planning. It is evaluated against the traditional decoupled planning approach in a make-to-order manufacturing environment. An industrial application of the S&OP model is provided using field data of an Oriented Strand Board (OSB) manufacturing company in Quebec, Canada.

**Keywords**. Sales and operations planning, supply chain management, optimization, make-to-order, oriented strand board industry.

**Acknowledgements.** The authors would like to acknowledge the financial support provided by the Forest E-business Research Consortium (FOR@c), University Laval, Québec, Canada, and would like to thank the research partners, Forintek Canada Corp. and our industrial partner Norbord Inc. Canada.



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* Corresponding author : Yan.Feng@cirrelt.ca

Dépôt légal – Bibliothèque nationale du Québec,
Bibliothèque nationale du Canada, 2007

## 1.0 Introduction

Faced with increasingly competitive markets within a dynamic economic environment, more and more enterprises have turned their attention to supply chain management. The concept of supply chain management is to bring the traditionally non-coordinated business units into a unified integrated organizational unit along the supply chain to effectively coordinate the business process from the suppliers to the customers. Along with supply chain management and supply chain planning, S&OP has gained increasing recognition.

S&OP is a monthly-based tactical planning process led by senior management oriented towards balancing demand and all the supply capabilities of production, distribution, procurement, and finance to ensure the plans and performances of all business functions are aligned to support the business plan. It is an integrated planning process that gathers all the plans from different functional units, evaluates, revises, and brings to consensus of any conflict to generate a unique set of plans to orchestrate and control the performance (Ling, 2002; Aberdeen Group, 2004; Bower, 2005). Since the 1990s, an increasing number of companies have started implementing S&OP process. Aberdeen Group (2004) presents a benchmark analysis of more than 200 enterprises of various sizes. The analysis reveals that S&OP programs generated significant improvements in gross margin, complete order fill rate, and customer retention. Aberdeen Group (2005) reports six best practice case studies on how different S&OP strategies and technologies improved the performance of each studied company. Palmatier and Crum (2003) state that companies adopting S&OP not only achieved improvement in operating performance and customer services, but also reduced manufacturing costs, purchased material costs and finish product inventory/customer order backlogs. Yet, in many cases, the S&OP effort fails to meet its potential expectations due to various reasons that raise certain risks to the companies who implement it (Muzumdar and Fontanella, 2006).

Until present time, most researches on S&OP have focused on its definition, processes and activities, implementation procedures, and case studies that address the benefit either qualitatively or quantitatively after the implementation. Very few contributions have addressed the S&OP problem using modeling approach to reveals its value creation opportunities before the implementation. The aim of our research is to fill in this gap by presenting a modeling approach that represents the fundamentals of the S&OP process to quantitatively evaluate the impact of S&OP program before the implementation.

In this article, we first explore two main dimensions of S&OP: (i) the horizontal cross functional integration of sales, production, distribution and procurement; and (ii) the vertical coordination between the tactical and operational planning decisions. Then, we propose an S&OP framework that integrates the various planning units in a coordinated and unified fashion. Following the framework, an optimization based S&OP model as well as a set of traditional non-coordinated models are formulated. The S&OP problem aims to maximize, over a planning horizon of one year, the total net profit of a multi-site company producing various products serving a diverse markets through different marketing channels. Our problem is centred in a make-to-order environment. The evaluation is focused on comparing the performance of S&OP with the non-coordinated planning models under deterministic demand and spot market price conditions. A numerical study and sensitivity analysis is carried out based on a case study of an OSB manufacturing company.

The main contribution of this paper is (i) the mathematical expression of the S&OP model which explicitly incorporates all the supply chain functions of sales, production, distribution and procurement of a multi-site organization in a make-to-order environment under deterministic demand and spot market conditions; and (ii) the industrial application, which presents some of the insight knowledge of the value of S&OP before its implementation.

## 2.0 Literature review

S&OP is a relatively new concept. Originally developed from production planning, early studies regard S&OP as a planning process that vertically links the strategic and business plans with the detailed operational plans and horizontally links and balances demand with supply capabilities with an emphasis on production capacity management (Ling and Goddard, 1988; Wallace, 2004). In order to provide a foundation for this research, we present the definition of S&OP from the APICS Dictionary (2002):

*"Sales and operations planning is the process with which we bring together all the plans for the business (customer, sales, marketing, development, manufacturing, sourcing, and financial) into one integrated set of plans. It is done at least once a month and reviewed by management at an aggregate (product family) level.*

*The process must reconcile all supply, demand, and new product plans at both the detail and aggregate level and tie to the business plan. It is a definitive statement of what the company plans to do for the near to intermediate term covering a horizon sufficient to plan resources and support the annual business planning process. Executed properly, the sales and operations planning process links the strategic plans for the business with execution and reviews performance measures for continuous improvement."* (Ling, 2002; Maiers and Thoreson, 2002; Taunton, 2002).

The presented definition defines explicitly what S&OP is from a process point of view. Note that the term "reconcile", means to bring to a state that is free of conflicts, inconsistencies, or differences, based on Merriam-Webster dictionary. Thus, the definition implies that S&OP is the process of developing an integrated aggregated plan, i.e. the S&OP plan that consists of a set of plans for each of the functional departments, incorporating the detailed level behaviors, and covering an intermediate term planning horizon. More precisely, it addresses the two dimensions of S&OP: (i) the horizontal cross functional integration, and (ii) the vertical coordination of the aggregated and detailed plans.

Recent studies present the trend of applying S&OP into the supply chain management context in coordinating supply chain value creation activities in order to profitably match the demand with the supply chain capabilities of production, distribution, procurement, and finance (Croxton et al., 2002; Cecere et al., 2006). Croxton et al. (2002) regard S&OP as a synchronization mechanism in the supply chain that matches the demand forecast to supply chain capabilities through coordination of marketing, manufacturing, purchasing, logistics and financing decisions and activities. The implication of synchronization is a waste free system, which reduces the system waiting time, resources, inventories to the minimum level while satisfying the customers' demands with the right quantity at the right time. Cecere et al. (2006) regard S&OP as a collaborative process that profitably aligns the customers' demands with the supplies against a defined business strategy. As such, the authors suggest that the S&OP plan should reflect supply chain constraints of moving, making and buying capabilities of the company. These constraints need to be tied with the account strategies for demand shaping and product allocation strategies. It implies that organizations should evolve from the effort of merely matching demand with supply of volume capabilities to the effort of determining the best and most profitable demand response with the available capabilities. The goal of the process is thus to create a realistic S&OP plan that best identifies the opportunities and effectively coordinates supply chain capabilities to achieve the company's objectives.

Although these literatures address the directions for S&OP, no research on S&OP, to the knowledge of the authors, has been carried out that systematically explores the fundamentals of the S&OP process using a modeling approach in a pre-implementation analysis. This stimulates us to study the literatures that address the coordination and integration of supply chain planning to discover the possibilities of applying operational research techniques and modeling approach into the S&OP process.

In a broad sense, the supply chain consists of three fundamental stages, production, distribution, and procurement (Thomas and Griffin, 1996). Traditionally, these stages have been managed independently, buffered with inventories. In this decoupled approach, decisions are made within each of the functional departments independently from one other. Although this approach reduces the complexity of the decision process, it ignores the interactions of the different stages, limits the potentials of further cost reduction and, in the worst case scenario, results in infeasible solutions. Facing the increasing competitions, companies are moving from decoupled decision making processes towards more coordinated and integrated planning and control for their supply chain activities in order to reduce total costs, improve performance, and increase service levels.

Although the concepts of Supply Chain Management (SCM) and S&OP are relatively new, the idea of coordinated planning can be traced back to as early as 1960 by Clark and Scarf (1960), who studied multi-echelon inventory/distribution systems. Since that time, research on coordination of various partial sections of the supply chain has been conducted. However, very few models have attempted to address the integration of sales, production, distribution and procurement simultaneously. The reasons are probably owing to technological limitations, as such a complete integration of the supply chain problem is difficult to solve. Most articles found so far focus on the integration of partially selected functions in the supply chain at planning or scheduling levels.

Williams (1981) studies the coordinated scheduling of production and distribution using a dynamic programming approach which simultaneously determines the production and distribution batch sizes that minimize the costs in an assembly and distribution network. Chandra and Fisher (1994) investigate the value of coordinating production scheduling and multi-stop vehicle routing to minimize set-ups, inventories and transportation costs. Youssef and Mahmoud (1996) propose a non-linear programming model considering production economies of scale to study the trade-offs between production and transportation costs and its impact on the facility centralization-decentralization decisions. Fumero and Vercellis (1999) propose a mixed-integer programming model for integrated production and distribution planning in order to optimally co-ordinate the capacity management, inventory allocation, and vehicle routing in a capacitated lot-sizing and multi-period vehicle routing problem. The feasible solution is compared to the solution generated by an alternative decoupled approach in which the production plan is developed first and the distribution schedule is derived consequently. The research indicates a substantial advantage of the integrated approach over the decoupled approach. Park (2005) uses a mixed-integer programming model investigates the effectiveness of the integrated production-distribution planning in a multi-plant, multi-retailer, and multi-period logistic environment under capacity constraints in order to maximize the total net profit. The results confirm that the integrated planning approach performs superior to the decoupled one. Dasci and Verter (2001) address the production-distribution system design problem and present a continuous approximation modeling framework, based on the use of continuous functions to represent spatial distributions of cost and customer demand. Cohen and Lee (1988) present a modeling framework and an analytic procedure that address the operating policies of material control, production, and distribution based on a hierarchical heuristic approach.

The applications of coordinated and integrated production-distribution planning in industrial environment have been documented in various publications. Klingman et al. (1988) develop an optimization programming based production-distribution planning system for the W.R. Grace company, making multi-commodity chemical products. Haq et al. (1991) propose an integrated production-inventory-distribution model in a multi-stage manufacturing system using mixed integer programming and applied to a real case of a company manufacturing urea fertilizer. Martin et al. (1993) present a large scale linear programming model of the production, distribution and inventory operation for a flat glass business of Libbey-Owens-Ford, in a multi-facility multi-product, multi-demand centre, and multi-period environment. The case study again shows a significant saving from the integrated planning approach. Chen and Wang (1997) developed a linear programming model to solve the integrated, procurement, production and distribution planning problem of a single planning period for a Canadian steel-making company in a multi-echelon logistic network under deterministic demand.

The coordination and integration of supply chain planning in the forest products industry have been studied intensively in recent years. Maness and Norton (2002) carry out research on the integration of lumber sales, sawing, inventory, and boom usage planning in sawmills. They develop a linear programming based multi-period planning model for the problem and tested it in a prototype sawmill assuming mill capacity, lumber prices, market demand, raw material supply are static over the planning period. Rizk et al. (2006) study the dynamic production-distribution planning problem in pulp and paper industry between a paper mill and a distribution centre with transportation costs subject to economies of scale following general piecewise linear functions. Ouhimmou et al. (2007) present an integrated planning model for the furniture industry that addresses the multi-site and multi-period planning of procurement, sawing, drying, and transportation. The MIP based model is solved both optimally using a CPLEX engine and approximately using time decomposition heuristics assuming a known and dynamic demand over the planning horizon.

Building on these previous works, we apply the concept of S&OP, incorporate sales decisions to investigate the opportunities of profitably matching and satisfying demand with the given supply chain capabilities of production, distribution, and procurement. More precisely, we propose a series of mathematical programming models to evaluate the benefit of the integrated S&OP

against the traditional decoupled planning process in a context of a real OSB manufacturing supply chain system within a make-to-order environment.

## 3.0 S&OP modeling framework

From the literature review of S&OP, three fundamental elements can be identified. First, S&OP is a cross functional integrated planning process; second, it facilitates the hierarchical coordination with the business plan and with the detailed scheduling; and third, it is a periodical on-going planning, reviewing and evaluation process that covers a planning horizon of one to two years. To successfully model the S&OP process, these three elements must be explicitly represented. We present a framework that describes the S&OP as an integrated tactical planning which integrates the supply chain decisions of sales, production, distribution and procurement into a unified planning system as shown in Figure 1.

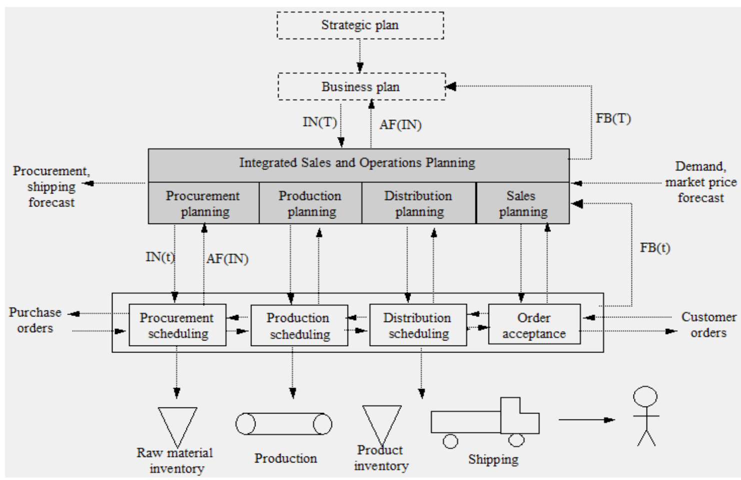


Figure 1. A generic schematic diagram of Sales and Operations Planning.

In the framework, the integrated S&OP serves as a bridging function that links the company's business plan and the detailed operation scheduling. The business plan provides the guideline or instructions IN(T) that set the constraints for the integrated S&OP for a planning horizon T. Integrated S&OP, embedded with an optimization algorithm, incorporating market intelligence, distribution costs, production constraints, productivities, raw material procurement constraints, etc., generates a set of feasible periodic plans for sales, production, distribution, and procurement that support the business plan in a timely and cost effective manner. Sales decisions play an important role in a company. They incorporate demand management that serves as a gateway which links the demand with supply chain activities of production, distribution, raw material procurement and supply. Its decisions not only affect revenues but also total cost. Thus, effective sales decisions require a cross functional supply chain analysis that balances revenues and total cost within the capabilities of the supply chain. From the literature review we note that sales decisions have been insufficiently studied.

At the other end, S&OP plans, in turn, set the rules and conditions, IN(t), for the decisions of order acceptance, resource allocations, lot sizing, inventory locations, and inventory quantities that coordinate the detailed level scheduling. The detailed order acceptance decisions decide, in real time, what order to accept given the capacity availability (capable-to-promise) that complies with the order acceptance rule. The detailed production, distribution, and procurement scheduling defines explicitly what, when, where, and how many to buy, make and ship. The detailed scheduling outlines the exact operation sequence that guides the supply chain execution in a synchronized manner.

The hierarchical coordination between integrated S&OP and detailed level scheduling is illustrated by anticipation AF(IN) of the S&OP model and periodic information feed back FB(t) from the detailed level scheduling. Anticipation is a planning strategy that can be used in the S&OP model that takes into account some of the relevant characteristics of the scheduling model in order to find feasible and optimal solutions. For instance, one of the common issues faced in tactical planning and operational scheduling in a process industry with constrained capacity is capacity planning. Tactical planning plans capacity and makes decisions based on the aggregated monthly demand and capacity availability. The plan, however, may result in an infeasible solution or a feasible solution with increased cost at the scheduling level due to varying weekly demands and fixed weekly capacity. In this case, an anticipation function AF(IN) can be embedded in the tactical planning model to anticipate the capacity reactions of the detailed level scheduling towards the tactical plan, IN(t). Anticipation is an important mechanism in hierarchical decision coordination within a distributed decision-making environment. The concept and modeling approach of anticipation is well addressed by Schneeweiss (2003). Feedback is the process where information regarding the state of operations at the end of the period, such as inventory levels or back orders, as well as the execution performance measures for the period are fed back to the integrated S&OP. It permits the integrated S&OP to update decisions for the following periods.

The dynamics of the S&OP process is modeled using a simulation model that encapsulates the integrated S&OP model as well as the detailed level scheduling models with linked database for data input, decision output and performance evaluation. It permits companies to emulate real planning activities in an industry facing stochastic demand and spot market price. The integrated S&OP model can also be used independently of scheduling models to support decisions at the aggregated tactical level. The proposed framework allows users to test different scenarios, such as demand changes and/or spot market price changes, by modifying one or several input parameters and to anticipate system performance. It can also be used as a decision support system to assist the company in making optimal decisions.

The framework is not limited to a single plant company. It can be applied to a multi-site enterprise where the integrated S&OP model supports the corporate with collaborative effort on centralized sales, production, distribution and procurement decisions incorporating demand and facility allocation (Figure 2). This centralized S&OP model will then generate a set of plans specific for each plant. Based on the corporate S&OP plans, each plant develops schedules locally for its own operations.

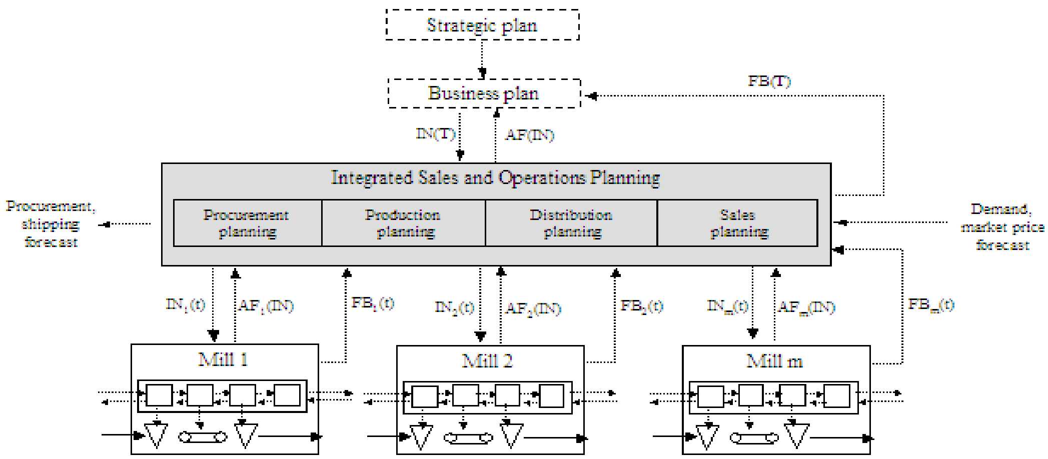


Figure 2. Sales and Operations Planning in multi-site enterprise environment.

It is believed that S&OP improves supply chain performance not only through cross functional integration and optimization, but also through hierarchical coordination processes. The integrated S&OP enables the synchronization of supply chain activities while the hierarchical coordination permits the system to react to the downstream changes quickly with optimal feasible solutions.

In this paper we develop an integrated S&OP model using mixed integer programming (MIP) for a general case of a multi-site manufacturing supply chain network with multi-customers and suppliers producing multiple products within a make-to-order environment. We also develop a set of non-coordinated MIP models to represent the traditional decoupled sales, production, distribution, and procurement planning on a single site basis. Both planning processes are then applied to an OSB manufacturing company that manufactures a broad range of products satisfying the demand in diverse North American market using different marketing channels of contract, non-contract, and spot market. An evaluation is given in section 6.0 to compare the two planning approaches under deterministic demands and spot market prices.

## 4.0 Model formulation

The S&OP problem considered in this paper consists of an enterprise in the processing industry with make-to-order operations. It has many mills (Figure 3) manufacturing multiple products and sell to its contract and non-contract customers, including spot markets, in different regions which are subject to different regional market prices. A contract demand is one received from a long-term customer with whom a contract is signed for an agreed price and quantity. Although the mills must satisfy the contract demand, they reserve the right of not satisfying the part that is beyond the agreed quantity, upon capacity shortage. A non-contract demand, including spot market, is one received from non-contract customers. This demand may not be satisfied, or not satisfied fully, when capacity is not available. The spot market, in the form of non-contract customers, serves as a buffer to absorb remaining capacities in a loosely "push" mode based on flexible demand. Both contract and non-contract demands are deterministic and dynamic with seasonality over the planning horizon. Unsatisfied demand is considered as lost in the model (but may re-appear as new demand in the following period in practice). Backorder is not allowed.

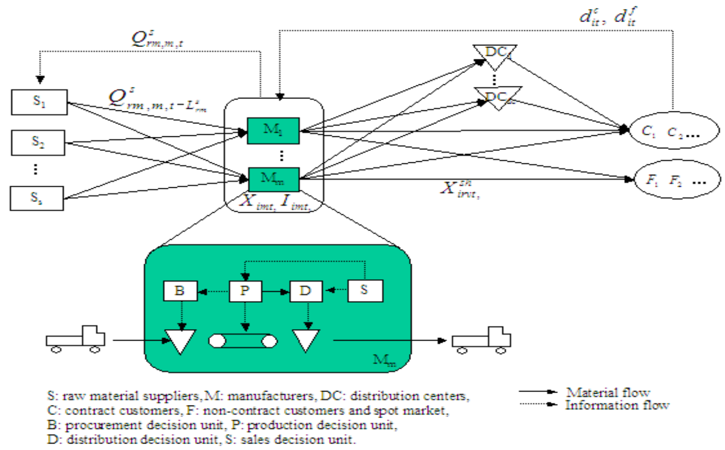


Figure 3. The supply chain network of the OSB manufacturing company.

Each mill is a self-managed business unit consisting of different functional units responsible for sales, production, distribution and procurement. Production is carried out in batch on a single machine with limited capacity. Each mill produces a number of product families. Each product family is produced using different raw materials at a specific quantity mix and production rates. Changing product families from one to another requires a sequence dependent set-up time which is independent from the volume produced. However, due to the small and insignificant differences at the aggregated level, the set-up time will be approximated as fixed and a fixed set-up cost will be considered. From each product family, different product items can be produced. Limited warehouse capacity is available at each mill to temporarily store the finished products.

Shipping is carried out by a number of third party logistic companies using different transportation modes (rail and truck) and different vehicle types and sizes. A fixed truckload cost per destination is charged for the rails, and a variable rate, for trucks. Final products are shipped to the customers either directly or indirectly via distribution centres (DCs). The enterprise has access to a set of DCs from the third party which are assumed to have unlimited capacity.

The enterprise procures raw materials from a set of contract and non-contract raw material suppliers. With a contract supplier, a minimum purchasing quantity must be complied under the agreed price over a planning horizon T. Some raw material supplies are subject to long lead-time, seasonality, and variability. Large raw material inventory capacity is available at each site to absorb the seasonality and variability of the supply. The raw material inventory is maintained and managed internally complying with safety stock and end of season inventory policies. Inbound raw material shipping cost is included in the procurement cost.

## 4.1 Modeling the cross functional S&OP system

Our problem is to develop an integrated S&OP model at aggregated product family level, that collaboratively unites the different manufacturing sites, coordinates the enterprise wide capacities, and integrates the cross functional planning of sales, production, distribution, and procurement for the entire enterprise. The aim is to maximize the total net profit over a planning horizon T. We formulate the integrated S&OP model using mixed integer programming. The indexes, sets, and parameters used in the model are listed below, followed by the decision variables:

**Indexes and sets**

T: Planning horizon, where t is a period $(t \in T)$

C: Set of contract customers where c is a contract customer $(c \in C)$

F: Set of "non-contract" customers where f is a non-contract customer, including spot market $(f \in F)$

M: Set of manufacturing mills, where m is a mill $(m \in M)$

I: Set of product families, where i is a product family $(i \in I)$

S: Set of raw material suppliers, where s is a supplier $(s \in S)$

G: Set of contract raw material suppliers $(s \in G)$ and $(G \subseteq S)$

RMC: Set of raw material categories, where rmc is a raw material category $(rmc \in RMC)$

RM: Set of raw materials, where rm is a raw material $(rm \in RM)$ and $(rm \in rmc)$

DC: Set of distribution centres, where dc is a distribution centre $(dc \in DC)$

SH: Set of outbound shipping suppliers, where sh is a shipper $(sh \in SH)$

V: Set of vehicle types, where v is a vehicle type $(v \in V)$

$R_{m,dc}$: Set of routes from mill m to distribution centre dc

$R_{m,c}$: Set of routes from mill m to customer c

$R_{m,f}$: Set of routes from mill m to customer f

$R_{dc,c}$: Set of routes from dc to customer c

$R_{dc,f}$: Set of routes from dc to customer f

R: Set of all routes where r is a route $(r \in R)$, and $R = R_{m,dc} \cup R_{m,c} \cup R_{m,f} \cup R_{dc,c} \cup R_{dc,f}$

**Parameters**

Sales:

$d^c_{it}$: demand from customer c for product family i in period t

$dmin^c_{it}$: minimum contract demand quantity from customer c for product family i in period t

$d^f_{it}$: demand from customer f for product family i in period t

$b^c_{it}$: sales price of product family i to customer c in period t

$b^f_{it}$: sales price of product family i to customer f in period t

Production:

$K_{mt}$: capacity of mill m in period t

$p_{im}$: capacity consumption for producing one batch of product family i at mill m

$\beta_{im}$: production batch size of product family i at mill m

$c_{im}$: unit production cost to produce product family i at mill m

$sc_m$: expected set-up cost at mill m

$st_m$: expected set-up time at mill m

$h_{im}$: inventory holding cost for unit quantity of product family i at mill m

$I_{im0}$: initial inventory of product family i in warehouse of mill m at t = 0

$KI_m$: warehouse inventory capacity of mill m

$G_i$: big number, $G_i \geq \max\left(\sum_{c\in C}\sum_{t\in T} d_{it}^{c} + \sum_{f\in F}\sum_{t\in T} d_{it}^{f}\right)$

Distribution:

$f_{rv}^{sh}$ : shipping fixed cost of supplier sh on route r using vehicle type v

$e_{irv}^{sh}$ : shipping variable cost of supplier sh for product family i on route r using vehicle type v

$a_i$: vehicle capacity absorption coefficient per unit of product family i

$h_{idc}$: inventory holding cost for unit quantity of product family i at distribution centre dc

$I_{idc0}$: initial inventory of product family i in distribution centre dc at t = 0

$tr_{idc}$: transhipment cost of unit quantity of product family i through distribution centre dc

$KSH_{vt}^{sh}$ : shipping capacity of supplier sh with vehicle v during period t

$KV_v$: vehicle capacity of vehicle type v

$KD_{mvt}$: expedition capacity of mill m for vehicle type v in period t

Procurement:

$u_{rm,i,m}$ : consumption of raw material rm for producing unit volume of product family i at mill m

$I_{rm,m,t_0}$ : raw material inventory of rm at mill m at the beginning of planning horizon $t = t_0$

$I_{rm,m,t_e}$ : raw material inventory target of rm at mill m at the end of period $t_e$, representing the inventory policy for the end of season and end of planning period

$KI_{rmc,m}$ : inventory capacity of raw material category rmc at mill m

$KS_t^s$ : supply capacity of supplier s in period t

$q\min^s$ : minimum contract purchase quantity from supplier s $(s \in G)$

$ss_{rmc,m,t}$ : safety stock of raw material category rmc at mill m in period t

$m_{rm,t}^{s}$ : unit purchase cost of raw material rm from supplier s in period t, including transportation cost

$sc_{rm}^{s}$ : setup cost of purchasing raw material rm from supplier s

$h_{rm,m}$ : inventory holding cost of raw material rm at mill m

$L_{rm}^{s}$ : lead time of procuring raw material rm from supplier s

$G_{rm}$: big number, $G_{rm} \geq \max\left(\sum_{s\in S}\sum_{t\in T} KS_t^s\right)$

**Decision variables**

Sales:

$S_{it}^{c}$: sales quantity of product family i to contract customer c in period t

$S_{it}^{f}$: sales quantity of product family i to non-contract customer f in period t

Production:

$X_{imt}$: production quantity of product family i at mill m in period t

$N_{imt}$: number of production batches of product family i at mill m in period t

$I_{imt}$ : inventory quantity of product family i in mill m at the end of period t

$$s_{imt} = \begin{cases} 1 & \text{if set up is required to produce product family i in period t, i.e., if } X_{imt} > 0, \\ 0 & \text{otherwise.} \end{cases}$$

Distribution:

$X^{sh}_{irvt}$ : shipping quantity of product family i by shipper sh on route r using vehicle v in period t

$N^{sh}_{rvt}$ : number of truckloads required from supplier sh delivering on route r using vehicle v in period t

$I_{idct}$ : inventory of product family i in dc at the end of period t

Procurement:

$Q^{s}_{rm,m,t}$ : purchasing quantity of raw material rm from supplier s by mill m in period t

$I_{rm,m,t}$ : inventory of raw material rm at mill m at the end of period t

$$y^{s}_{rm,t} = \begin{cases} 1 & \text{if a purchase is made for material rm from supplier s, i.e. } Q^{s}_{rm,m,t} > 0, \\ 0 & \text{otherwise.} \end{cases}$$

The objective function of the model is to maximize the net profit of the contract and non-contract sales taking into consideration of the total cost of production, distribution and procurement for a multi-site enterprise over the planning horizon T.

Max

$$\left(\sum_{c\in C}\sum_{i\in I}\sum_{t\in T} b^{c}_{it} S^{c}_{it} + \sum_{f\in F}\sum_{i\in I}\sum_{t\in T} b^{f}_{it} S^{f}_{it}\right) -$$
$$\left(\sum_{i\in I}\sum_{m\in M}\sum_{t\in T} c_{im} X_{imt} + \sum_{i\in I}\sum_{m\in M}\sum_{t\in T} sc_{m} s_{imt} + \sum_{i\in I}\sum_{m\in M}\sum_{t\in T} h_{im} I_{imt}\right) -$$
$$\left(\sum_{sh\in SH}\sum_{i\in I}\sum_{r\in R}\sum_{v\in V}\sum_{t\in T}\left(e^{sh}_{irv} X^{sh}_{irvt} + f^{sh}_{rv} N^{sh}_{rvt}\right) + \sum_{sh\in SH}\sum_{i\in I}\sum_{r\in R_{m,dc}}\sum_{v\in V}\sum_{t\in T} tr_{idc} X^{sh}_{irvt} + \sum_{i\in I}\sum_{dc\in DC}\sum_{t\in T} h_{idc} I_{idct}\right) -$$
$$\left(\sum_{rm\in RM}\sum_{s\in S}\sum_{m\in M}\sum_{t\in T} m^{s}_{rm,t} Q^{s}_{rm,m,t} + \sum_{rm\in RM}\sum_{s\in S}\sum_{t\in T} sc^{s}_{rm} y^{s}_{rm,t} + \sum_{rm\in RM}\sum_{m\in M}\sum_{t\in T} h_{rm,m} I_{rm,m,t}\right) \quad (1)$$

The first bracket represents the total revenue from the total sales. The second bracket states the production, set up, and inventory costs. The third bracket describes the variable and fixed transportation costs, the dc transhipment and dc inventory costs. The inventory in DCs is included in the integrated model in order to provide the flexibility to the capacity management upon dynamic demand. It can be set to zero to represent strict make-to-order operation with DCs being used as transhipment centres only. The last bracket presents the costs of purchasing, order set-up, and raw material inventory. The inbound transportation cost is included in the procurement cost that reflects the normal practice of the industry.

Constraints (2) and (3) describe the sales decisions for contract demand stating that a contract demand that is above the base amount for the period t may not be fully satisfied because of the lack of capacity from the mills. They also imply that the company has the option, upon satisfaction of the base amount, to continue serving the contract demand up to the capacity limit, or to switch to serve non-contract demand, whichever is more profitable.

$$S_{it}^{c} \geq d\min_{it}^{c} \qquad \forall c,i,t \qquad (2)$$

$$S_{it}^{c} \leq d_{it}^{c} \qquad \forall c,i,t \qquad (3)$$

Constraints (4) present the non-contract sales decisions that a non-contracted demand may not be satisfied or satisfied fully.

$$S_{it}^{f} \leq d_{it}^{f} \qquad \forall f,i,t \qquad (4)$$

Constraints (5) and (6) are the coupling constraints that connect the sales and distribution decisions together, stating that sales quantities must be equal to the total shipments to customers.

$$S_{it}^{c} = \sum_{sh\in SH} \sum_{r\in(R_{m,c}\cup R_{dc,c})} \sum_{v\in V} X_{irvt}^{sh} \qquad \forall c,i,t \qquad (5)$$

$$S_{it}^{f} = \sum_{sh\in SH} \sum_{r\in(R_{m,f}\cup R_{dc,f})} \sum_{v\in V} X_{irvt}^{sh} \qquad \forall f,i,t \qquad (6)$$

The set of production constraints are illustrated by (7) to (11). Constraints (7) ensure that the production is always in full batches. Constraints (8) are the production capacity constraints stating that the total production and set-up time should not exceed the total available time in the planning period t. Constraints (9) are the inventory capacity constraints describing that the total product inventories must not exceed warehouse capacity. Constraints (10) imply that if there is a production of product family i, there must be a set-up for it. Constraints (11) are the coupling constraints that connect the production and distribution decisions together. They state that the total production quantity from a mill m plus the beginning inventory minus the ending inventory must be equal to the total shipment delivered out of the mill in that period.

$$X_{imt} = N_{imt}\beta_{im} \qquad \forall i,m,t \qquad (7)$$

$$\sum_{i\in I} p_{im} N_{imt} + \sum_{i\in I} st_{m} s_{imt} \leq K_{mt} \qquad \forall m,t \qquad (8)$$

$$\sum_{i\in I} I_{imt} \leq KI_{m} \qquad \forall m,t \qquad (9)$$

$$G_{i} s_{imt} \geq X_{imt} \qquad \forall i,m,t \qquad (10)$$

$$X_{imt} + I_{imt-1} - I_{imt} = \sum_{sh\in SH} \sum_{r\in(R_{m,c}\cup R_{m,f}\cup R_{m,dc})} \sum_{v\in V} X_{irvt}^{sh} \qquad \forall i,m,t \qquad (11)$$

The distribution constraints are described by constraints (12) to (15) in which constraints (12) are the flow conservation constraints for the DCs. They state that the total shipments delivered to a DC plus the beginning inventory minus the ending inventory must be equal to shipments delivered out of the DC in period t. Constraints (13) calculate the number of truckloads required of each vehicle type from each supplier to meet the needs of total shipments. They describe that each load may contain multiple products for the same destination, and a less than truck load is possible, however, the objective function force this variable to take the smallest integer value that satisfies the constraints. Constraints (14) are the shipping supplier capacity constraints, and (15), the mill dispatch capacity constraints.

$$\sum_{sh\in SH} \sum_{r\in R_{m,dc}} \sum_{v\in V} X_{irvt}^{sh} + I_{idct-1} - I_{idct} = \sum_{sh\in SH} \sum_{r\in(R_{dc,c}\cup R_{dc,f})} \sum_{v\in V} X_{irvt}^{sh} \qquad \forall i,dc,t \qquad (12)$$

$$N_{rvt}^{sh} \geq \sum_{i\in I} \frac{a_i X_{irvt}^{sh}}{KV_v} \qquad \forall sh,r,v,t \qquad (13)$$

$$\sum_{r\in R} N^{sh}_{rvt} \le KSH^{sh}_{vt} \qquad \forall sh,v,t \qquad (14)$$

$$\sum_{sh\in SH} \sum_{r\in(R_{m,c}\cup R_{m,f}\cup R_{m,dc})} \sum_{v\in V} N^{sh}_{rvt} \le KD_{mt} \qquad \forall m,t \qquad (15)$$

Constraints (16) to (22) present the procurement constraints where constraints (16) are the coupling constraints that connect the raw material deliveries and inventory balances with the material usage in the production. The delivery quantity is the purchasing quantity that was ordered in period $t - L^{s}_{rm}$. Constraints (17) state that the material procured from a contract supplier must satisfy the contract quantity commitment. The material supply capacity constraints are described by constraints (18). Supplier capacity is presented as a function of t in order to incorporate the seasonal variability of the supply. Constraints (19) are the order set-up constraints. It is assumed that orders for multiple plants can be coordinated to reduce the order set-up cost. The raw material inventory capacity constraints are illustrated in constraints (20) and the safety stock constraints are described in constraints (21). Constraints (22) represent the policy the company may have for the season ending inventory. Finally, the non-negative variable and binary variable constraints are presented in constraints (23) that define the domain for the variables.

$$\sum_{s\in S} Q^{s}_{rm,m,t-L^{s}_{rm}} + \mathrm{I}_{\mathrm{rm,m,t\text{-}1}} - I_{rm,m,t} = \sum_{i\in I} u_{rm,i,m} X_{imt} \qquad \forall rm,m,t = 1-L^{s}_{rm},\ldots,T \qquad (16)$$

$$\sum_{m\in M}\sum_{rm\in RM}\sum_{t\in T} Q^{s}_{rm,m,t} \ge q\min^{s} \qquad \forall s\in G \qquad (17)$$

$$\sum_{rm\in RM}\sum_{m\in M} Q^{s}_{rm,m,t} \le KS^{s}_{t} \qquad \forall s,t \qquad (18)$$

$$G_{rm} y^{s}_{rm,t} \ge \sum_{m\in M} \mathrm{Q}^{s}_{\mathrm{rm,m,t}} \qquad \forall\, s,rm,t \qquad (19)$$

$$\sum_{rm\in rmc} I_{rm,m,t} \le KI_{rmc,m} \qquad \forall\, rmc,m,t \qquad (20)$$

$$\sum_{rm\in rmc} I_{rm,m,t} \ge ss_{rmc,m,t} \qquad \forall\, rmc,m,t \qquad (21)$$

$$I_{rm,m,t=t_e} \le I_{rm,m,t_e} \qquad \forall\, rm,m,t_e \qquad (22)$$

$$S^{c}_{it},\, S^{f}_{it},\, X_{imt},\, N_{imt},\, I_{imt},\, X^{sh}_{irvt},\, N^{sh}_{rvt},\, I_{idct},\, Q^{s}_{rm,m,t},\, I_{rm,m,t} \ge 0,\; N_{imt} \text{ and } N^{sh}_{rvt} \text{ are integers}$$

$$s_{imt} \in \{0,1\},\, y^{s}_{rm,t} \in \{0,1\} \qquad \forall c,f,i,m,t,sh,r,v,dc,s,rm \qquad (23)$$

### 4.2 Modeling the decoupled planning system

In this section, the decoupled planning models are developed in which each mill is an independent business entity. Each mill receives its own demands, $d^{c}_{imt}$ and $d^{f}_{imt}$ and makes its own sales decisions, $S^{c}_{imt}$ and $S^{f}_{imt}$, as well as production, distribution, and procurement decisions. The decisions are made separately by different functional units within the mill. Each functional unit seeks optimal decisions locally. In distribution planning, although all mills have access to the common DCs, each mill manages its own shipments through DCs which are used as transhipment centres only. Global performance as an enterprise is the combined performance of each mill. The set of decoupled planning models for each mill is represented as follows.

**Sales-Production model:**

In the make-to-order environment, sales planning and production capacity planning are often connected and can be considered as a joint model. Sales decisions are intended to maximize profit under the capacity constraints through contract and non-contract sales, while taking consideration of the production, set-up, and inventory costs. The model is:

$$\text{Max: } \left(\sum_{c\in C}\sum_{i\in I}\sum_{t\in T} b_{it}^{c} S_{imt}^{c} + \sum_{f\in F}\sum_{i\in I}\sum_{t\in T} b_{it}^{f} S_{imt}^{f}\right) - \left(\sum_{i\in I}\sum_{t\in T} c_{im} X_{imt} + \sum_{i\in I}\sum_{t\in T} sc_{m} s_{imt} + \sum_{i\in I}\sum_{t\in T} h_{im} I_{imt}\right) \quad \forall m \qquad \text{(S1)}$$

Subject to constraints: (7), (8), (9), and (10) plus

$$S_{imt}^{c} \geq d\min_{imt}^{c} \quad \forall c,i,m,t \qquad \text{(S2)}$$

$$S_{imt}^{c} \leq d_{imt}^{c} \quad \forall c,i,m,t \qquad \text{(S3)}$$

$$S_{imt}^{f} \leq d_{imt}^{f} \quad \forall f,i,m,t \qquad \text{(S4)}$$

$$X_{imt} + I_{imt-1} - I_{imt} = \sum_{c\in C} S_{imt}^{c} + \sum_{f\in F} S_{imt}^{f} \quad \forall i,m,t \qquad \text{(S11)}$$

$$S_{imt}^{c}, S_{imt}^{f}, X_{imt}, N_{imt}, I_{imt} \geq 0,\ N_{imt} \text{ is integer, and } s_{imt} \in \{0,1\} \quad \forall c,f,i,m,t \qquad \text{(S23)}$$

Constraints (S2), (S3), and (S4) are the modified constraints of (2), (3), and (4) where demand and sales decisions are limited to each individual mill. Constraints (S11) modified constraints (11) that remove the coupling variable of shipment and replaced by the sales decision variables. Constraints (S23) are the modified non-negative constraints pertaining only to the sales and production decision variables. The problem can be solved to optimality. The sales and production plan derived from the model are served as input parameters in the following distribution and the procurement models, respectively.

**Distribution model:**

The distribution model makes decisions concerning the shipping suppliers, the number of vehicles required, and the routes (direct shipping or indirect shipping through a DC) for the mill m with the objective function being to minimize the total distribution cost. The model is:

$$\text{Min: } \sum_{sh\in SH}\sum_{i\in I}\sum_{v\in V}\sum_{t\in T}\left(\sum_{r\in R}\left(e_{irv}^{sh} X_{irvt}^{sh} + f_{rv}^{sh} N_{rvt}^{sh}\right) + \sum_{r\in R_{m,dc}} tr_{idc} X_{irvt}^{sh}\right) \quad \forall m \qquad \text{(D1)}$$

Subject to constraints: (13), (14), and (15) plus (D5), (D6), (D12) and the non-negative constraints (D23). Constraints (D5) and (D6) are the modified constraints of (5) and (6) where the sales decisions are from a single mill. Constraints (D12) modify constraints (12) by removing the DC inventories. Constraints (D23) are the modified non-negative constraints that only take the distribution decision variables into consideration. It is important to note that the sales, production, and inventory quantities in constraints (D5), (D6), and (11) are the parameters determined previously by the sales-production model to which the distribution model has no further influence.

$$S^{c}_{imt} = \sum_{sh \in SH} \sum_{r \in (R_{m,c} \cup R_{dc,c})} \sum_{v \in V} X^{sh}_{irvt} \qquad \forall c,i,m,t \qquad \text{(D5)}$$

$$S^{f}_{imt} = \sum_{sh \in SH} \sum_{r \in (R_{m,f} \cup R_{dc,f})} \sum_{v \in V} X^{sh}_{irvt} \qquad \forall f,i,m,t \qquad \text{(D6)}$$

$$\sum_{sh \in SH} \sum_{r \in R_{m,dc}} \sum_{v \in V} X^{sh}_{irvt} = \sum_{sh \in SH} \sum_{r \in (R_{dc,c} \cup R_{dc,f})} \sum_{v \in V} X^{sh}_{irvt} \qquad \forall i,dc,t \qquad \text{(D12)}$$

$$X^{sh}_{irvt}, N^{sh}_{rvt} \geq 0, \text{ and } N^{sh}_{rvt} \text{ is integers }, \qquad \forall sh,i,r,v,t \qquad \text{(D23)}$$

**Procurement model:**

The procurement model decides which materials, from which suppliers, at what quantities to purchase and how many inventories to keep for the mill m with the objective function being to minimize the procurement cost

$$\text{Min: } \left( \sum_{rm \in RM} \sum_{s \in S} \sum_{t \in T} m^{s}_{rm,t} Q^{s}_{rm,m,t} + \sum_{rm \in RM} \sum_{s \in S} \sum_{t \in T} sc^{s}_{rm} y^{s}_{rm,t} + \sum_{rm \in RM} \sum_{t \in T} h_{rm,m} I_{rm,m,t} \right) \quad \forall m \qquad \text{(B1)}$$

subject to constraints (16), (20), (21), and (22) plus (B17), (B18), (B19) and non-negative constraints (B23). Constraints (B17), (B18) and (B19) modify constraints (17), (18), and (19) to illustrate the procurement decisions of a single mill. The parameter $q\min^{s}$ in constraints (17) now becomes $\bar{q}\min^{s}_{m}$ representing an estimated share of the contract commitment of mill m. The material supply constraints (18) are now described by (18B) having the procurement quantity calculated on a single mill basis. The order set-up costs in constraints (B19) are now charged for any purchase order made from a single mill. Constraints (B23) are the modified constraints (23) that include only the variables relevant to the procurement decisions. Similar to the distribution model, the production quantities in constraints (16) are now the parameters determined previously by the sales-production model to which the procurement model has no further influence. The problem can then be solved to optimality.

$$\sum_{rm \in RM} \sum_{t \in T} Q^{s}_{rm,m,t} \geq \bar{q} \min^{s}_{m} \qquad \forall s \in G, m \qquad \text{(17B)}$$

$$\sum_{rm \in RM} Q^{s}_{rm,m,t} \leq KS^{s}_{t} \qquad \forall s,m,t \qquad \text{(18B)}$$

$$G y^{s}_{rm,t} \geq \mathrm{Q}^{s}_{\mathrm{rm,m,t}} \qquad \forall s,rm,m,t \qquad \text{(B19)}$$

$$Q^{s}_{rm,m,t}, I_{rm,m,t} \geq 0, \text{ and } y^{s}_{rm,t} \in \{0,1\} \qquad \forall s,rm,m,t \qquad \text{(B23)}$$

## 5.0 Application to an OSB industry case

### 5.1 Case description

The models described in section 4 were developed in the context of a project that was carried out in collaboration with a large OSB panel manufacturing company having 11 manufacturing mills across North America and Europe. Although the integrated S&OP model is for the multiple sites, it can easily be adopted in a single site enterprise environment. This section presents a case where the S&OP concept and model have been applied to one of its OSB mills, in Quebec, Canada. The problem scope consists of one manufacturing mill producing 11 product families using 8 raw materials supplied by 19 raw material suppliers. Products are shipped to 140 customers across 5 different regions by 8 shipping companies using 5 different vehicle types via 2 distribution centres. The performances of the integrated S&OP model is compared with the non-coordinated planning models based on the data obtained from the company.

OSB is a wood composite product made from wood strands, synthetic resins and wax. It is primarily used as building material for wall, roof, and floor sheathings as well as I-joists. The mill in the study produces products mainly for wall and roof sheathings as well as web stocks used for making I-Joists. It has a single production line with a bottleneck machine, called multi-daylight hot press, which operates around the clock, throughout the year. In the production line, the wood logs of different species (Aspen, Birch, and Balsam Poplar) are fed into the system according to specific proportions. These logs are debarked and stranded. The wood strands are separated into two streams of face and core materials that are dried to different moisture content specifications, respectively. The dried wood strands are mixed with wax and different resins, in liquid and powder forms, specially formulated for using in the face and core layers, respectively. The mixture of the wood strands is then formed into mattresses that are pressed under high temperature and pressure in the hot press to produce well bonded and consolidated structural panels. In each pressing cycle, a batch of full press load panels of the same product family must be produced. These panels are then cut into different sizes, packed and stored in warehouse to be shipped to the customers. The company has an internal warehouse with limited inventory capacity. The inventory is considered as part of the process to cool down the products and a temporary storage place for products waiting to be shipped. Thus, the inventory cost is included in the production cost.

The production line produces 11 different product families. Each has specific physical and mechanical properties as well as jumbo panel dimensions. As a result, each product family requires a unique quantity mix of raw materials ($u_{rm,\ i,\ m}$) and is produced based on a defined pressing sequence and cycle time ($p_{im}$), as shown in Figure 4. A change of product family from one to another requires a set-up time which varies depending on the product family being produced before and immediately after. The set-up cost is estimated based on the production loss due to the set-up time and its expected market value. A weighed average of product market values is used to determine the set-up cost. From each product family, depending on the cutting pattern used, different cut-to-size panels (product items) can be produced that are packed and sold to customers in different regions at different prices $b^{c}_{it}$ and $b^{f}_{it}$ (Figure 4). Consequently, the sales decision plays an important role, since it not only impacts the revenue, but also the productivity, as well as the total cost of production, distribution and procurement.

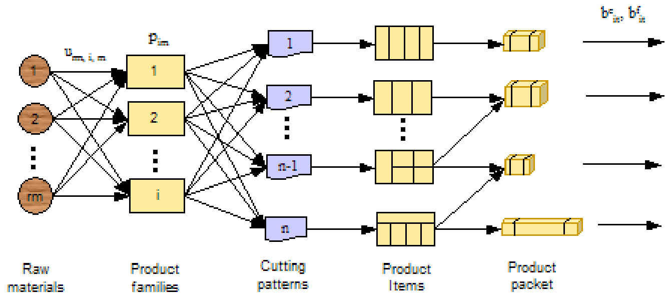


Figure 4. Product structure.

The company has two categories of demand, contract and non-contract. In this industry, companies generally sign annual contracts or agreements or commitments for a percentage of annual capacity. Remaining sales are made by selling to non-contract customers and the spot market in different geographical regions at dynamic regional market prices. Contract sales provide ongoing sales at a pre-negotiated price. However, it locks the capacity and the price which limits the company from getting greater revenue when the market price is high. Non-contract and spot market sales, on the other hand, although usually with higher prices, are riskier, since prices may substantially decrease and quantities are not guaranteed. In this industry, both contract and non-contract demands are highly seasonal which influence spot market prices. Therefore, it is important to decide what percentage of the capacity should be allocated to contract sales and what percentage to the non-contract sales, with the aim being to secure the market yet have the flexibility of taking advantage of the favourable spot market price.

Shipments are made using both rail and trucks of different vehicle types, by a number of third party shipping companies. For the purpose of this numerical study, a flat truckload rate is used for all shipments. Orders are shipped either directly to the customers or through DCs. The DCs are used for reloading purposes i.e., to divide large loads into smaller loads or combine smaller loads into large ones.

Wood supply for production is sourced from various sources. Approximately 50% of the wood supply is from Canadian crown land through an agreement called CAAF (*Contrat d'approvisionnement et d'aménagement forestier*). A CAAF grants the right for the company to harvest the agreed volume of stems from the crown land for a period of one year at an agreed price. The company must comply with the agreement. Harvesting operations and inbound transportation are carried out by contractors. The other 50% is from private timberland owners as well as the spot market. Wood supply from crown land and private timber lands generally has a long lead time of one month on average, while from the spot market the delivery can be made immediately after the purchase. Although the spot market generally has lower prices and shorter lead-time, availability is not always guaranteed. Wood supply in Quebec is affected by seasonality that varies considerably over the year due to changes in the weather. In the forest, more wood is harvested during winter season because during this time, the ground is frozen that there is no need for road construction and there is little risk of damaging when hauling logs out of the forest. In April and May, wood supply is scarce because log transportation in forest is prohibited due to thawing. During summer, operations are focused on silvicultural management and relatively less wood is harvested (Carlsson et al., 2007). Resin and wax supplies are not affected by seasonality and have short lead time. They are also purchased from contract and non-contract suppliers. While the contract supply provides the guarantee for the material availability, the non-contract supply helps to balance the prices and provides volume flexibilities. We consider that all raw material inbound transportations are provided by the suppliers. The shipping cost is included in the procurement cost.

## 5.2 Experimental design

This section describes the plan used for evaluating the performance of an integrated S&OP against the non-coordinated planning approaches. The evaluation is first conducted based on the actual system data obtained from the company for 2005 in order to validate both the integrated and non-coordinated models. Following the validation, both planning models were evaluated using generated demands and spot market prices under 54 different scenarios with 6 factors as shown in Table (1) and (2). The figure 0% represents the base level of the factor, while the -10%, -20%, 10% or 20% represent the factor being reduced by 10%, 20% or increased by 10% or 20% respectively.

Table 1. Experimental design.

(1) With different levels of spot market price, demand, and unit procurement unit cost.

| | Factors | | |
|---|---|---|---|
| Scenarios | Spot market price | Demand | Unit procurement cost |
| 1, 2, 3, | -20% | -10% | -10%, 0%, 10% |
| 4, 5, 6, | | 0% | -10%, 0%, 10% |
| 7, 8, 9, | | 10% | -10%, 0%, 10% |
| 10, 11, 12, | -10% | -10% | -10%, 0%, 10% |
| 13, 14, 15, | | 0% | -10%, 0%, 10% |
| 16, 17, 18, | | 10% | -10%, 0%, 10% |
| 19, 20, 21, | 0% | -10% | -10%, 0%, 10% |
| 22, 23, 24, | | 0% | -10%, 0%, 10% |
| 25, 26, 27, | | 10% | -10%, 0%, 10% |
| 28, 29, 30, | 10% | -10% | -10%, 0%, 10% |
| 31, 32, 33, | | 0% | -10%, 0%, 10% |
| 34, 35, 36 | | 10% | -10%, 0%, 10% |

(2) With different levels of shipping capacity, production cycle time and inventory capacity.

| | Factors | | |
|---|---|---|---|
| Scenarios | Shipping capacity | Production cycle time | Inventory capacity |
| 37, 38, 39, | 0% | -10% | -20%, 0%, 20% |
| 40, 41, 42, | | -5% | -20%, 0%, 20% |
| 43, 44, 45, | | 0% | -20%, 0%, 20% |
| 46, 47, 48, | 20% | -10% | -20%, 0%, 20% |
| 49, 50, 51, | | -5% | -20%, 0%, 20% |
| 52, 53, 54 | | 0% | -20%, 0%, 20% |

Sensitivity analysis is carried out using the generated data to study how individual parameters affect the benefits of integrated S&OP. The parameters examined include different levels of spot market price, demand, unit production cost, unit procurement cost, unit shipping costs, raw material inventory holding cost, product inventory capacity, production cycle time, and shipping capacity as shown in Table 2.

Table 2. Sensitivity analysis testing plan.

| Factors | Levels | | | | |
|---|---|---|---|---|---|
| Spot market unit price | -20% | -10% | 0% | 10% | 20% |
| Demand | -20% | -10% | 0% | 10% | 20% |
| Unit production cost | -20% | -10% | 0% | 10% | 20% |
| Unit procurement cost | -20% | -10% | 0% | 10% | 20% |
| Unit shipping cost | -20% | -10% | 0% | 10% | 20% |
| Raw material inventory holding cost | -20% | -10% | 0% | 10% | 20% |
| Product inventory capacity | -20% | -10% | 0% | 10% | 20% |
| Production cycle time | -10% | -5% | 0% | -- | -- |
| Shipping capacity | -- | -- | 0% | 10% | 20% |

## 5.3 Demand generation algorithms

With the lack of historical real demand records in the system, actual weekly shipping data is used to approximate customer ordering information and to derive their ordering behaviours. We then generate customer demand based on their ordering behaviours. Both contract and non-contract customers exhibited seasonality in their ordering. However, they followed different behaviours. Contract demands usually arrive regularly at a fixed ordering interval. Although the expected total annual demand is known with high certainty, the exact periodic demand varies randomly and is influenced by seasonality. The demand generation algorithm for contract demand is presented as follows:

<u>Algorithm A:</u>

Step 1. determine the ordering interval $I_i^c$ for product family i from customer c, starting week $\tau_0$ and ending week $\tau_e$.

Step 2. set $\tau \leftarrow \tau_0$.

Step 3. generate an ordering quantity $d_{i\tau}^{c}{}'$ for week τ from customer c ordering product family i, following normal distribution $N_{i\tau}^c\left(\mu_{i\tau}^c, \sigma_{i\tau}^c\right)$.

Step 4. increment τ to $\tau \leftarrow \tau + I_i^c$ and check if $\tau \leq \tau_e$, if yes, go to step 3, if no, go to step 5.

Step 5. apply seasonality factors $s_{i\tau}^c$ to the generated ordering quantities to determine the seasonal demand $d_{i\tau}^c = s_{i\tau}^c d_{i\tau}^c{}'$. For customers having no seasonality, their seasonal factor $s_{i\tau}^c = 1$.

Step 6. aggregate the weekly ordering quantity $d_{i\tau}^c$ to derive the monthly demand quantities $d_{it}^c$ to be used as the demand input for the models.

Step 7. repeat the procedure from step 1 to 6 for every customer $c \in C$ and product family $i \in I$.

The non-contract demands, on the other hand, arrive irregularly with some influences from seasonality. The order quantity is also influenced by seasonality. Thus, the demand generation follows different algorithm presented as:

Algorithm B:

Step 1. generate a total ordering quantity $d_{iT}^{f}$ for product family i from a customer f for the planning horizon T following normal distribution $N_{iT}^{f}\left(\mu_{iT}^{f},\sigma_{iT}^{f}\right)$, and set remaining quantity $R \leftarrow d_{iT}^{f}$.

Step 2. determine the ordering seasonality probability for customer f ordering product family i in each week τ, $P_i^f(\tau)$, starting week $\tau_0$ and ending week $\tau_e$. For orders without seasonality, a uniform distribution $U_i^f(0,1)$ is used.

Step 3. flip an ordering week τ following the seasonality probability $P_i^f(\tau)$ or $U_i^f(0,1)$ within the planning horizon T[$\tau_0$, $\tau_e$].

Step 4. Generate an ordering quantity $d_{i\tau}^{f}$ for week τ from customer f ordering product family i following normal distribution $N_{i\tau}^{f}\left(\mu_{i\tau}^{f},\sigma_{i\tau}^{f}\right)$. Calculate the remaining quantity $R \leftarrow R - d_{i\tau}^{f}$, and check if $R \le 0$. If yes, go to Step 5, otherwise got to Step 3.

Step 5. aggregate the weekly ordering quantity $d_{i\tau}^{f}$ to derive the monthly demand quantities $d_{it}^{f}$ to be used as the demand input for the models.

Step 6. repeat the procedure from step 1 to 6 for every customer $f \in F$ and product family $i \in I$.

Using these demand generation methods, non-contract demand does not arrive every week, especially in low season periods. In high season period, demand may arrive several times in the same week from the same customer for the same product family. When this happens, the multi-orders are summed to derive the weekly order quantity to reflect one order per week practice. Moreover, it is possible that more orders (both contract and non-contract) are generated in one period, causing capacity shortage, while fewer orders are generated in another causing capacity surplus. It reflects the real demand situation faced by the companies in this industry.

## 5.4 Spot market price generation

The spot market price analysis is carried out based on the Random Lengths Panel Price for the year 2005 provided by the company. Random Lengths prices provide a guideline for commodity products selling to non-contract customers. The generation of the spot market price follows the contract demand generation procedure in algorithm A with a fixed weekly interval $I_i^r$. The un-seasonalized weekly price $b_{i\tau}^{r}{}'$ for product family i in region r week τ is generated following normal distribution $N_{i\tau}^{r}\left(\mu_{i\tau}^{r}\ \sigma_{i\tau}^{r}\right)$. A set of seasonality factors are then applied to the weekly price to derive the seasonal price $b_{i\tau}^{r} = s_{i\tau}^{r} b_{i\tau}^{r}{}'$. Based on the weekly seasonal price $b_{i\tau}^{r}$, the monthly spot market price $b_{it}^{r}$ is calculated by averaging the weekly prices of region r within the month. The monthly spot market price for a non-contract customer f in region r for product family i is derived as $b_{it}^{f}$.

The contract price is determined based on the most current three month rolling average of the spot market price for the region where the customer belongs. The contract price for customer c, product family i, in month t can be expressed by the formula $\left( b_{it}^{c} = \frac{1}{3}\sum_{t=t-2}^{t} b_{it}^{r} + \Delta a \right)$, where $\Delta a$ is a coefficient representing any additional adjustment to the price for specialty products with special treatments. It is zero for standard products.

All demands and spot market prices are generated using the FOR@C experimental platform. The models are solved using CPLEX 10.0 optimization engine with branch and bound algorithm through optimization programming language OPL5.0. The programs are run on Windows Platform using Intel Pentium 4 workstation with CPU 2.40 GHz, 512 MB of RAM, and Windows XP Home Edition Version 2002.

## 6.0 Computational results and discussions

### 6.1 Model validation

Both integrated and decoupled models are preliminarily validated using field data obtained from the company. Table 3 shows the validation results of the decoupled models. The nominal capacity is the designed capacity of the mill and the demand used is the company's actual shipping quantity as explained earlier in section 5.3. From the results, we can see that the total sales and production quantities derived from the decoupled models are very close to the nominal capacity and demand, resulting in a service level of 99.8%. The capacity utilization is 91.8% indicating 8% of capacity is not used which is in agreement with the expected percentage of unplanned downtime. These results confirm the validity of the models.

Table 3. Validation results

| | Values (sqf. 1/16" basis) |
|---:|---|
| Nominal capacity: | 2,100,000,000 |
| Demand in 2005: | 2,127,882,660 |
| Total sales quantity from the decoupled model: | 2,123,737,250 |
| Total production quantity from the decoupled model: | 2,123,746,800 |
| Service level from the decoupled model: | 99.8% |
| Capacity utilization from the decoupled model: | 91.8% |

### 6.2 Results and discussions

The evaluation of the benefits of the integrated model against the decoupled models is made by comparing the following performance criteria: annual profit, revenue, revenue from the contract sales, revenue from the non-contract sales, production cost, transportation cost, procurement cost, service level and capacity utilization. Due to the confidentiality agreement, the evaluation presented here is based on simulated demands and spot market prices generated using algorithms A and B. Table 4 shows the benefit of the integrated model, calculated by 100*(value of integrated model – value of decoupled model)/value of decoupled model. As expected, the integrated model generates higher annual profit than the decoupled models. The higher annual profit is resulted from the fact that the integrated model dropped some non-contract sales while adding some contract sales. Although this caused a total revenue reduction, it reduced total production, distribution and procurement costs, and resulted in a net profit improvement. In other words, if these "unjustified" sales had been accepted, it would have resulted in a total net profit loss. The reduced sales quantity of the integrated model results in a slight reduction in customer service level (Table 4) and capacity utilization. To maintain the same service level or increase it often has cost implications. The modeling approach allows the company to make better cost-benefit analysis in assessing different decisions. The relatively smaller benefit between the integrated and decoupled approaches is owing to the strong market conditions during which the case was conducted and the fact that both the integrated and decoupled models are optimization based models.

Table 4. The benefit of the integrated S&OP model.

| Performance criteria | Benefit (%) | Benefit ($CAD) |
|---|---|---|
| Annual profit | 0.8% | 548,080 |
| Total revenue | -0.5% | -694,000 |
| Revenue from contract sales | 0.9% | 1,057,600 |
| Revenue from non-contract sales | -10.3% | -1,751,490 |
| Production cost | -0.4% | -97,810 |
| Transportation cost | -8.9% | -871,561 |
| Procurement cost | -0.8% | -273,920 |
| Service level | -- | -0.8% |
| Capacity utilization | -- | -0.4% |

Table A-1 and Table A-2 in appendixes present the benefit of the integrated model, in percentage and CAD value respectively, under different scenarios following the experimental plan shown in Table 1, together with the solution gap and CPU time for solving the integrated model. In all cases, the integrated model generates greater profit than the decoupled planning models. The greater profit is largely owing to the cost reductions, especially the transportation cost reduction, ranging from 5.7 to 19.2% and valuing from $528,565 CAD to $1,928,706 CAD. This result is in agreement with many previous publications addressing the coordination and integration of production-distribution planning (Chandra and Fisher, 1994; Fumero and Vercellis, 1999). In our case however, due to the complexity of the problem, the integrated production-distribution model addressing partial supply chain problems would not be sufficient. In many situations, the procurement cost reduction cannot be ignored. As shown in Table A-1 and Table A-2, the integrated S&OP model provides far richer information than the partial supply chain planning models.

The benefit of the integrated S&OP model varies in relation to the market conditions and supply chain costs. Figure 5 demonstrates the impact of market demand, price, and raw material unit procurement cost on the profit increase. Spot market price has the greatest impact on the benefit of the integrated S&OP model, particularly when price is low and unit procurement cost is high (Figure 5). When price is low, the decoupled sales-production model would make the sales decision that maximize profit taking only the production capacity and cost into the consideration, without explicitly considering the effect of down stream distribution and procurement costs. Often, such a decision would easily contribute to the un-justified sales that increase revenues, but also the down-stream costs to a greater extent, resulting in a total net profit loss. The integrated model, on the other hand, makes the sales decisions taking considerations of the revenues it generates and also of the total supply chain cost, thus minimizing the "unjustified sales". A similar trend is observed at all demand levels. The greatest benefit occurs when the spot market price is low and the unit procurement cost is high with a higher level of demand (Figure 5). A higher demand level increases the demand population size that allows greater freedom in sales decisions for both integrated and decoupled models. However, when the spot market price is low, the integrated model would have greater benefit comparatively due to its integrated approach. The interactions of spot market price, unit shipping cost and unit procurement cost at different levels are shown in Figure 6. As expected, the benefit of the integrated model increases as the unit shipping cost increases with the greatest benefit occuring when the spot market price is low, the unit shipping and procurement costs are high. Particular attention is paid to the unit procurement cost in the analysis due to its greater weighing in this industry. As shown in Figure 7, procurement cost accounts for over 50% of the total annual cost.

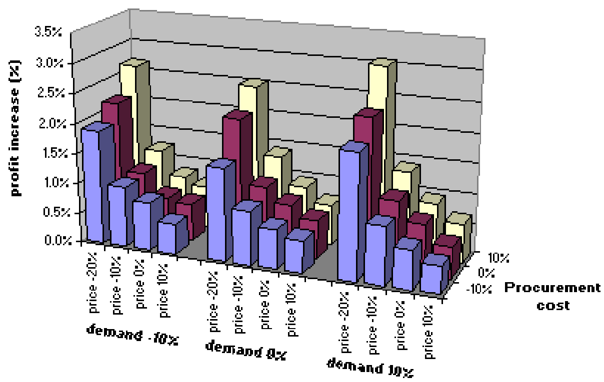


Figure 5. The benefit of the integrated model at different levels of spot market price, demand and raw material procurement cost.

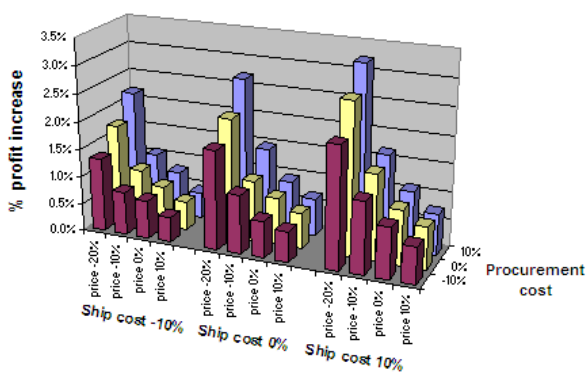


Figure 6. The benefit of the integrated model at different levels of spot market price, unit shipping and procurement costs.

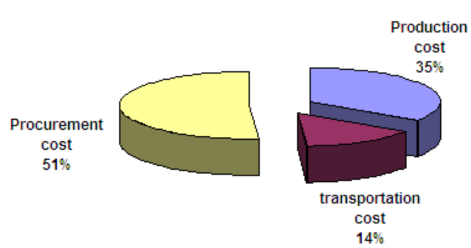


Figure 7. Cost breakdown in percentage.

The benefit of the integrated model in relation to different supply chain capacities is shown in Figure 8. The capacities studied are capacities of production (by means of pressing cycle time), product inventory, and shipping. Pressing cycle time is a technology dependent factor that relates to the combination of equipment capabilities, production control and product design. Due to the limited capacity of the hot press, greater efforts are placed on reducing the pressing cycle time as it directly increases productivity. As a result, reducing pressing cycle time has been regarded as an alternative approach to increase production capacity. Reducing pressing cycle time may result in down stream capacity deficiencies. In our case, when pressing cycle time is reduced by 10%, existing shipping capacity becomes insufficient causing decoupled distribution model having infeasible solutions. Additional shipping capacity has to be added in order to have feasible solutions, as shown in the dotted bar in Figure 8.

From Figure 8, we can observe that when pressing cycle time is at its base level, the benefit of the integrated model changes rather insignificantly as inventory and shipping capacities change. This is because when the pressing cycle time is at its base level, the inventory and shipping capacities are sufficient to meet the production and shipping requirements in both integrated and decoupled models. Varying the inventory and shipping capacities at the given ranges has little impact to further benefit increases. As the pressing cycle time decreases, the benefit of the integrated model decreases when inventory capacity is high and increases when inventory capacity is low. This is because when pressing cycle time decreases, the increased productivity relaxes some capacity constraints, especially in high demand periods, allowing more demand quantities being satisfied in both the integrated and decoupled models. During low demand periods, high inventory capacity allows more production quantities to be stored as inventory (for the following high demand period) resulting in higher sales quantities in both the integrated and decoupled models, thus a reduced gap. When inventory capacity is low, higher productivity is restricted by the low inventory capacity in the decoupled sales-production model, especially during low demand period, resulting in reduced sales. The integrated model, on the other hand, with the flexibility of keeping inventories in DCs, allows high productivity to be fully utilized, and therefore, has more sales and benefits than the decoupled models. A similar trend is evident in both low and high shipping capacity levels.

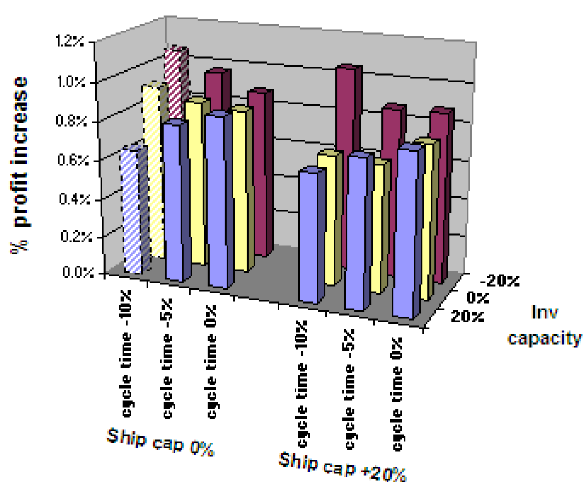


Figure 8. The benefit of integrated model at different levels of production cycle time, shipping capacity, and product inventory capacity.

### 6.3 Sensitivity analysis

In this section, we present the sensitivity analysis results and discuss how the individual input parameters outlined in Table 2 affect the benefit of the integrated model. Figure 9 illustrates how the benefit changes as each individual parameter changes. In this analysis, the parameter change is limited to the global change, that is, if the spot market price increases by 10%, the price for all products in all regions during all periods of the planning horizon increase by 10%.

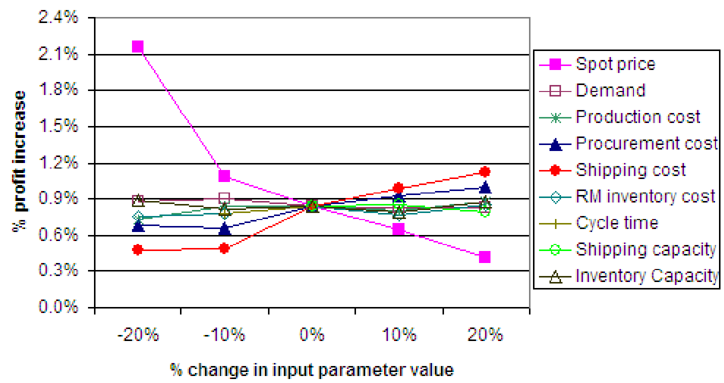


Figure 9. Sensitivity analysis of the benefit of an integrated S&OP approach.

From the graph, we can observe that the benefit of the integrated model is most sensitive to the spot market price as represented by the steepest slope where the benefit decreases as the spot market price increases. This result is in agreement with the ones shown in Figure 5 and Figure 6. When the spot market price is low, the revenues of both contract and non-contract sales are low, with the total cost unchanged, the integrated model will drop the unjustified sales that would have been accepted by the decoupled models to reduce profit loss. Therefore, when spot market price is low, the integrated model tends to have greater benefit. As the spot market price increases, the unjustified sales quantity decreases. The profit of the integrated model is getting close to that of the decoupled models, therefore, a reduced benefit.

The benefit of the integrated model is also sensitive to shipping and procurement costs, but not as sensitive to production cost. This is because both the decoupled and integrated models integrate sales and production decisions, and the change of production cost alone makes little difference to the benefit of the integrated model. For shipping and procurement costs however, since decoupled sales-production model makes sales and production decisions separately from the distribution and procurement decisions, the down stream shipping and procurement cost increases are not considered in the sales-production model. Based on the sales and production decisions made in the sales-production model, the shipping and procurement models must satisfy them at all costs. The integrated model, on the other hand, makes decisions taking all the price-cost tradeoffs in sales, production, distribution and procurement into consideration, which in effect, finds solutions that maximize profit. As a result, the benefit of the integrated model increases as the unit shipping and procurement costs increase.

Comparing to spot market price, shipping and procurement costs, the benefit of the integrated model is less sensitive to demand, production cost, raw material inventory cost, cycle time, shipping and inventory capacities. In other words, the benefit of the integrated model is relatively constant as each of these parameters changes individually.

## 7.0 Conclusions

In this article, the concept of S&OP is discussed focusing on the cross functional integration and hierarchical coordination of the aggregated tactical planning and operational scheduling. An S&OP modeling framework is developed for a single-plant organization, which is then extended to a multi-plant organization. A generalized mixed integer programming formulation is developed to model the integrated S&OP of sales, production, distribution, and procurement for a multi-plant organizational supply chain network. The traditional decoupled and non-coordinated planning approach is also modeled under the multi-plant organization context. Both planning models are applied to an industrial case of an OSB manufacturing plant and evaluated using field data obtained from the plant.

The goal is to develop the S&OP framework and models, which will allow companies to evaluate the benefit of the S&OP process before its implementation. The computational results from 54 scenarios show that the integrated planning outperforms the decoupled planning in all cases. The benefit varies as market conditions and supply chain costs change. The benefit ranges from 0.5% to 3.1% valuing from $372,000 to $1,200,000 (Table A-1 and Table A-2). Our sensibility analysis reveals that the benefit of the integrated S&OP model is sensitive to spot market prices, and unit shipping and procurement costs. Therefore, these parameters need to be estimated with greater precision.

This article presents the performance evaluation using only a small number of scenarios where each parameter changes globally. However, it is possible that these parameters change locally, i.e. price increases in one region, or demand increases for one particular product only, etc. These are some examples that one often faces in real business environment. The models provide companies with the ability to analyse different scenarios in real life and support them in making feasible and optimal supply chain decisions.

## Acknowledgements

The authors would like to acknowledge the financial support provided by the Forest E-business Research Consortium (FOR@C), University Laval, Quebec, Canada, and would like to thank the research partners, Forintek Canada Corp. and our industrial partner Norbord Inc. Canada.

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## Appendixes

Table A- 1. The benefit of the integrated S&OP model in % of the performance criteria,

(1) At different levels of market price, demand, and unit purchase cost.

| | Levels | | | Performance criteria | | | | | | | Solution measures | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenarios | Price | Demand | Procurement unit cost | Profit | Revenue | Contract revenue | Non-contract revenue | Production cost | Transportation cost | Procurement cost | MIP gap | Time (sec) |
| 1 | -20% | -10% | -10% | 1.9% | -1.7% | 0.1% | -14.2% | -2.4% | -12.9% | -2.5% | 0.44% | 228 |
| 2 | -20% | -10% | 0% | 2.2% | -2.0% | 0.1% | -16.1% | -2.8% | -13.9% | -2.8% | 0.46% | 291 |
| 3 | -20% | -10% | 10% | 2.7% | -3.0% | 0.1% | -24.3% | -4.1% | -17.0% | -4.1% | 0.54% | 428 |
| 4 | -20% | 0% | -10% | 1.5% | -2.2% | 1.1% | -25.2% | -2.6% | -14.9% | -2.9% | 0.61% | 709 |
| 5 | -20% | 0% | 0% | 2.2% | -2.2% | 0.8% | -23.7% | -2.9% | -15.5% | -3.0% | 0.41% | 224 |
| 6 | -20% | 0% | 10% | 2.5% | -3.4% | 1.0% | -34.4% | -4.4% | -19.2% | -4.5% | 0.58% | 406 |
| 7 | -20% | 10% | -10% | 2.1% | -1.5% | 1.5% | -24.3% | -2.1% | -13.9% | -2.3% | 0.42% | 585 |
| 8 | -20% | 10% | 0% | 2.4% | -1.8% | 1.5% | -26.8% | -2.4% | -15.0% | -2.6% | 0.45% | 611 |
| 9 | -20% | 10% | 10% | 3.1% | -3.0% | 1.6% | -37.6% | -4.0% | -19.1% | -4.3% | 0.43% | 454 |
| 10 | -10% | -10% | -10% | 1.0% | -0.6% | 0.0% | -4.4% | -0.7% | -7.7% | -1.0% | 0.42% | 335 |
| 11 | -10% | -10% | 0% | 1.0% | -1.0% | 0.0% | -7.7% | -1.3% | -9.6% | -1.5% | 0.46% | 348 |
| 12 | -10% | -10% | 10% | 1.2% | -1.5% | 0.0% | -11.3% | -2.0% | -11.4% | -2.1% | 0.46% | 402 |
| 13 | -10% | 0% | -10% | 0.9% | -0.7% | 0.9% | -11.8% | -0.6% | -8.9% | -0.9% | 0.52% | 398 |
| 14 | -10% | 0% | 0% | 1.1% | -1.2% | 0.9% | -15.7% | -1.3% | -11.2% | -1.6% | 0.45% | 282 |
| 15 | -10% | 0% | 10% | 1.4% | -1.7% | 0.9% | -19.8% | -2.1% | -13.5% | -2.4% | 0.42% | 555 |
| 16 | -10% | 10% | -10% | 1.0% | -0.7% | 1.4% | -15.9% | -0.7% | -9.5% | -0.9% | 0.35% | 326 |
| 17 | -10% | 10% | 0% | 1.2% | -1.2% | 1.5% | -20.4% | -1.4% | -11.6% | -1.6% | 0.36% | 451 |
| 18 | -10% | 10% | 10% | 1.4% | -1.7% | 1.6% | -25.6% | -2.2% | -14.0% | -2.4% | 0.34% | 436 |
| 19 | 0% | -10% | -10% | 0.8% | -0.3% | 0.1% | -2.8% | -0.3% | -6.9% | -0.6% | 0.38% | 254 |
| 20 | 0% | -10% | 0% | 0.7% | -0.4% | 0.0% | -3.1% | -0.4% | -6.7% | -0.6% | 0.47% | 589 |
| 21 | 0% | -10% | 10% | 0.8% | -0.6% | -0.1% | -3.5% | -0.7% | -7.6% | -0.9% | 0.45% | 547 |
| 22 | 0% | 0% | -10% | 0.7% | -0.5% | 0.9% | -9.8% | -0.3% | -8.5% | -0.6% | 0.38% | 752 |
| 23 | 0% | 0% | 0% | 0.8% | -0.5% | 0.9% | -10.3% | -0.4% | -8.9% | -0.8% | 0.28% | 406 |
| 24 | 0% | 0% | 10% | 0.9% | -0.6% | 1.0% | -11.4% | -0.5% | -8.9% | -0.9% | 0.34% | 373 |
| 25 | 0% | 10% | -10% | 0.7% | -0.5% | 1.4% | -13.9% | -0.4% | -8.3% | -0.6% | 0.35% | 617 |
| 26 | 0% | 10% | 0% | 0.8% | -0.5% | 1.6% | -14.7% | -0.5% | -8.5% | -0.7% | 0.32% | 397 |
| 27 | 0% | 10% | 10% | 0.9% | -0.5% | 1.5% | -14.3% | -0.5% | -8.9% | -0.7% | 0.29% | 431 |
| 28 | 10% | -10% | -10% | 0.5% | -0.2% | 0.0% | -1.8% | -0.3% | -5.7% | -0.4% | 0.30% | 535 |
| 29 | 10% | -10% | 0% | 0.6% | -0.2% | 0.1% | -2.3% | -0.2% | -6.1% | -0.4% | 0.31% | 629 |
| 30 | 10% | -10% | 10% | 0.7% | -0.2% | 0.1% | -2.5% | -0.3% | -6.2% | -0.5% | 0.32% | 340 |
| 31 | 10% | 0% | -10% | 0.5% | -0.3% | 0.6% | -6.5% | -0.1% | -7.3% | -0.3% | 0.33% | 926 |
| 32 | 10% | 0% | 0% | 0.6% | -0.4% | 0.9% | -9.3% | -0.2% | -8.5% | -0.6% | 0.27% | 272 |
| 33 | 10% | 0% | 10% | 0.7% | -0.4% | 0.8% | -9.0% | -0.2% | -8.3% | -0.7% | 0.29% | 362 |
| 34 | 10% | 10% | -10% | 0.5% | -0.2% | 1.1% | -9.5% | -0.2% | -6.2% | -0.3% | 0.35% | 513 |
| 35 | 10% | 10% | 0% | 0.5% | -0.4% | 1.4% | -12.7% | -0.3% | -7.3% | -0.5% | 0.32% | 520 |
| 36 | 10% | 10% | 10% | 0.7% | -0.3% | 1.5% | -12.8% | -0.2% | -7.5% | -0.5% | 0.29% | 708 |

(2) At different levels of shipping capacity, pressing cycle time, and inventory capacity.

| | Levels | | | Performance criteria | | | | | | | Solution measures | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenarios | Shipping capacity | Pressing cycle time | Inventory capacity | Profit | Revenue | Contract revenue | Non-contract revenue | Production cost | Transportation cost | Procurement cost | MIP gap | Time (sec) |
| 37 | 0% | 0% | -20% | 0.9% | -0.5% | 0.9% | -10.3% | -0.4% | -9.0% | -0.8% | 0.27% | 262 |
| 38 | 0% | 0% | 0% | 0.8% | -0.5% | 0.9% | -10.3% | -0.4% | -8.9% | -0.8% | 0.28% | 406 |
| 39 | 0% | 0% | 20% | 0.9% | -0.5% | 0.9% | -10.5% | -0.4% | -9.1% | -0.8% | 0.29% | 361 |
| 40 | 0% | -5% | -20% | 1.0% | -0.4% | 0.3% | -5.2% | -0.5% | -8.6% | -0.7% | 0.31% | 109 |
| 41 | 0% | -5% | 0% | 0.9% | -0.4% | 0.3% | -5.3% | -0.5% | -7.8% | -0.7% | 0.31% | 585 |
| 42 | 0% | -5% | 20% | 0.8% | -0.5% | 0.2% | -4.9% | -0.4% | -7.9% | -0.7% | 0.58% | 852 |
| 43 | 0% | -10% | -20% | 1.1% | -0.1% | 0.4% | -3.4% | 0.0% | -6.8% | -0.3% | 0.33% | 420 |
| 44 | 0% | -10% | 0% | 0.9% | -0.4% | 0.0% | -2.9% | -0.4% | -7.7% | -0.7% | 0.29% | 127 |
| 45 | 0% | -10% | 20% | 0.7% | -0.5% | 0.0% | -3.7% | -0.6% | -7.2% | -0.7% | 0.43% | 765 |
| 46 | 20% | 0% | -20% | 0.9% | -0.5% | 0.8% | -9.7% | -0.4% | -9.0% | -0.8% | 0.29% | 246 |
| 47 | 20% | 0% | 0% | 0.8% | -0.5% | 0.9% | -10.1% | -0.4% | -8.4% | -0.8% | 0.34% | 524 |
| 48 | 20% | 0% | 20% | 0.8% | -0.5% | 0.8% | -9.9% | -0.4% | -8.8% | -0.8% | 0.31% | 408 |
| 49 | 20% | -5% | -20% | 0.9% | -0.4% | 0.3% | -5.2% | -0.4% | -7.9% | -0.7% | 0.31% | 452 |
| 50 | 20% | -5% | 0% | 0.7% | -0.5% | 0.3% | -5.8% | -0.5% | -7.0% | -0.8% | 0.55% | 476 |
| 51 | 20% | -5% | 20% | 0.8% | -0.4% | 0.2% | -5.0% | -0.4% | -7.4% | -0.7% | 0.40% | 563 |
| 52 | 20% | -10% | -20% | 1.1% | -0.2% | 0.4% | -3.7% | -0.1% | -7.6% | -0.4% | 0.43% | 337 |
| 53 | 20% | -10% | 0% | 0.7% | -0.6% | -0.2% | -2.7% | -0.6% | -7.8% | -0.8% | 0.47% | 482 |
| 54 | 20% | -10% | 20% | 0.7% | -0.5% | -0.1% | -3.2% | -0.5% | -7.1% | -0.7% | 0.47% | 660 |

Table A- 2. The benefit of the integrated S&OP model in $CAD of the performance criteria,

(1) At different levels of market price, demand, and unit purchase cost.

| | Levels | | | Performance criteria | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenarios | Price | Demand | Procurement unit cost | Profit | Revenue | Contract revenue | Non-contract revenue | Production cost | Transportation cost | Procurement cost |
| 1 | -20% | -10% | -10% | 745,564 | -1,751,380 | 120,430 | -1,871,810 | -533,510 | -1,199,463 | -766,160 |
| 2 | -20% | -10% | 0% | 798,164 | -2,057,970 | 60,330 | -2,118,300 | -631,900 | -1,288,417 | -939,370 |
| 3 | -20% | -10% | 10% | 894,104 | -3,088,590 | 111,550 | -3,200,140 | -928,340 | -1,583,509 | -1,472,460 |
| 4 | -20% | 0% | -10% | 657,475 | -2,358,580 | 1,063,570 | -3,422,150 | -631,550 | -1,465,490 | -923,500 |
| 5 | -20% | 0% | 0% | 851,465 | -2,438,370 | 784,640 | -3,223,010 | -686,040 | -1,526,870 | -1,077,130 |
| 6 | -20% | 0% | 10% | 921,055 | -3,715,983 | 952,350 | -4,668,333 | -1,042,890 | -1,885,655 | -1,718,460 |
| 7 | -20% | 10% | -10% | 939,432 | -1,754,670 | 1,519,400 | -3,274,070 | -520,830 | -1,396,550 | -779,660 |
| 8 | -20% | 10% | 0% | 1,023,122 | -2,077,058 | 1,535,100 | -3,612,158 | -614,480 | -1,506,703 | -980,800 |
| 9 | -20% | 10% | 10% | 1,195,162 | -3,465,653 | 1,600,100 | -5,065,753 | -1,015,160 | -1,928,706 | -1,720,570 |
| 10 | -10% | -10% | -10% | 512,782 | -667,930 | -24,730 | -643,200 | -158,050 | -718,506 | -306,310 |
| 11 | -10% | -10% | 0% | 504,692 | -1,178,370 | -39,840 | -1,138,530 | -301,510 | -891,693 | -495,580 |
| 12 | -10% | -10% | 10% | 562,282 | -1,704,390 | -37,490 | -1,666,900 | -456,380 | -1,059,539 | -754,390 |
| 13 | -10% | 0% | -10% | 501,395 | -814,780 | 982,800 | -1,797,580 | -139,260 | -879,375 | -301,650 |
| 14 | -10% | 0% | 0% | 565,905 | -1,404,360 | 985,900 | -2,390,260 | -303,440 | -1,105,743 | -567,820 |
| 15 | -10% | 0% | 10% | 684,855 | -2,039,100 | 978,200 | -3,017,300 | -498,460 | -1,325,597 | -907,080 |
| 16 | -10% | 10% | -10% | 562,884 | -902,310 | 1,608,800 | -2,511,110 | -188,780 | -965,283 | -312,130 |
| 17 | -10% | 10% | 0% | 641,024 | -1,493,940 | 1,729,700 | -3,223,640 | -363,950 | -1,179,100 | -594,060 |
| 18 | -10% | 10% | 10% | 736,254 | -2,209,060 | 1,835,000 | -4,044,060 | -563,730 | -1,423,910 | -960,250 |
| 19 | 0% | -10% | -10% | 501,733 | -383,760 | 69,400 | -453,160 | -75,410 | -640,015 | -175,610 |
| 20 | 0% | -10% | 0% | 404,343 | -503,470 | 8,600 | -512,070 | -88,920 | -625,433 | -202,160 |
| 21 | 0% | -10% | 10% | 474,333 | -707,300 | -140,800 | -566,500 | -149,000 | -703,829 | -331,020 |
| 22 | 0% | 0% | -10% | 446,610 | -668,060 | 998,800 | -1,666,860 | -74,860 | -832,864 | -209,200 |
| 23 | 0% | 0% | 0% | 548,080 | -693,890 | 1,057,600 | -1,751,490 | -97,810 | -871,561 | -273,920 |
| 24 | 0% | 0% | 10% | 574,040 | -773,170 | 1,155,600 | -1,928,770 | -112,070 | -878,486 | -358,980 |
| 25 | 0% | 10% | -10% | 472,915 | -667,820 | 1,783,800 | -2,451,620 | -90,510 | -843,441 | -211,510 |
| 26 | 0% | 10% | 0% | 570,705 | -653,130 | 1,940,300 | -2,593,430 | -114,840 | -862,121 | -248,030 |
| 27 | 0% | 10% | 10% | 620,185 | -715,020 | 1,812,000 | -2,527,020 | -136,290 | -903,293 | -297,700 |
| 28 | 10% | -10% | -10% | 371,608 | -336,490 | -10,800 | -325,690 | -57,260 | -528,565 | -126,660 |
| 29 | 10% | -10% | 0% | 445,338 | -292,020 | 117,900 | -409,920 | -49,980 | -570,079 | -125,110 |
| 30 | 10% | -10% | 10% | 484,308 | -331,130 | 124,900 | -456,030 | -64,720 | -572,449 | -182,920 |
| 31 | 10% | 0% | -10% | 436,955 | -405,760 | 812,300 | -1,218,060 | -29,720 | -721,369 | -94,510 |
| 32 | 10% | 0% | 0% | 496,925 | -591,970 | 1,138,600 | -1,730,570 | -50,420 | -836,514 | -203,710 |
| 33 | 10% | 0% | 10% | 509,795 | -615,210 | 1,069,500 | -1,684,710 | -55,500 | -815,458 | -257,760 |
| 34 | 10% | 10% | -10% | 392,559 | -377,050 | 1,482,600 | -1,859,650 | -45,190 | -629,597 | -97,600 |
| 35 | 10% | 10% | 0% | 427,639 | -570,180 | 1,907,400 | -2,477,580 | -67,210 | -744,548 | -189,560 |
| 36 | 10% | 10% | 10% | 526,709 | -470,780 | 2,020,200 | -2,490,980 | -56,520 | -760,752 | -188,180 |

(2) At different levels of shipping capacity, pressing cycle time, and inventory capacity.

| | Levels | | | Performance criteria | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenarios | Shipping capacity | Pressing cycle time | Inventory capacity | Profit | Revenue | Contract revenue | Non-contract revenue | Production cost | Transportation cost | Procurement cost |
| 37 | 0% | 0% | -20% | 573,216 | -696,210 | 1,044,100 | -1,740,310 | -106,010 | -889,858 | -277,410 |
| 38 | 0% | 0% | 0% | 548,080 | -693,890 | 1,057,600 | -1,751,490 | -97,810 | -871,561 | -273,920 |
| 39 | 0% | 0% | 20% | 568,872 | -696,750 | 1,087,200 | -1,783,950 | -98,750 | -892,267 | -281,980 |
| 40 | 0% | -5% | -20% | 635,867 | -603,770 | 299,300 | -903,070 | -110,820 | -872,411 | -256,380 |
| 41 | 0% | -5% | 0% | 571,675 | -596,870 | 330,900 | -927,770 | -115,910 | -791,473 | -267,920 |
| 42 | 0% | -5% | 20% | 535,093 | -634,150 | 214,100 | -848,250 | -106,930 | -797,018 | -265,330 |
| 43 | 0% | -10% | -20% | 712,092 | -102,860 | 514,400 | -617,260 | 10,550 | -703,385 | -125,180 |
| 44 | 0% | -10% | 0% | 619,238 | -536,660 | -2,500 | -534,160 | -110,980 | -796,276 | -249,830 |
| 45 | 0% | -10% | 20% | 438,788 | -709,520 | -33,000 | -676,520 | -142,120 | -740,730 | -268,230 |
| 46 | 20% | 0% | -20% | 569,676 | -682,664 | 968,692 | -1,651,356 | -106,546 | -876,353 | -269,426 |
| 47 | 20% | 0% | 0% | 510,621 | -673,970 | 1,038,000 | -1,711,970 | -94,860 | -823,768 | -269,410 |
| 48 | 20% | 0% | 20% | 532,583 | -700,888 | 981,744 | -1,682,632 | -95,010 | -857,892 | -280,560 |
| 49 | 20% | -5% | -20% | 573,393 | -587,550 | 314,700 | -902,250 | -104,880 | -791,051 | -269,600 |
| 50 | 20% | -5% | 0% | 434,833 | -666,580 | 337,100 | -1,003,680 | -119,450 | -701,194 | -282,850 |
| 51 | 20% | -5% | 20% | 500,314 | -598,880 | 273,300 | -872,180 | -101,520 | -745,869 | -255,250 |
| 52 | 20% | -10% | -20% | 703,269 | -224,010 | 450,400 | -674,410 | -13,880 | -782,740 | -135,390 |
| 53 | 20% | -10% | 0% | 452,353 | -796,100 | -296,300 | -499,800 | -154,370 | -797,784 | -300,750 |
| 54 | 20% | -10% | 20% | 439,635 | -678,950 | -104,100 | -574,850 | -135,340 | -732,184 | -269,400 |