Methodology for using real-time process data for cost modeling and supply chain decision support in the pulp and paper industry

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Abstract: With the implementation of mill-wide information management systems, process and cost data have become increasingly available. Careful analysis and use of this data to model critical production processes can be useful for supply chain (SC) optimization. This paper presents a modeling approach which integrates both process and cost information. Operations-driven costing is used to represent how resources are consumed by process activities, and how process activities are related to cost objects. The “bottom-up” methodology is illustrated for the SC optimization of a pulp mill, for different levels of logistical management.

The growth potential for the pulp and paper industry in North America is limited. Industry leaders are faced with the challenge of defining business and technology strategies that will not just help the industry survive, but also prosper in the long run. Some proposed strategies for success include advanced product and process automation, debottlenecking of processes, supply chain optimization, and maintaining high environmental standards [1]. The industry, which must provide consistently good returns to shareholders and invest carefully in business and technology strategies, generally recognizes three main overall business strategies [2]:
1. Survival in commodities,
2. Buy/build in emerging markets,
3. Diversify core business with marketing and technological partners.

In the supply chain management context, the first strategy entails developing tools and systems to optimize the overall supply chain in order to join ranks with the most cost-effective producers. With the second strategy, significant benefits may be achieved by exploiting the potential synergies of a worldwide network of assets using supply chain concepts. The third strategy is related to the maximization of the existing carbon value chain, in order to optimally capture the value of a tree, including bark, lignin and wood fibre for paper, energy, and chemicals [3].

One of the basic and most essential elements for these strategies is to operate efficiently, reduce costs and inventories, and capture the synergy of intra- and inter-company integration and management. This can be achieved using supply chain management (SCM) concepts for the optimization of the enterprise and its supply chain. Supply chain (SC) is defined by Chopra and Meindl [4] as “the complete set of activities, resources and information needed to plan, source, manufacture, store, sell and deliver products to customers”, (Fig. 1). Therefore, SCM involves the design, coordination, and management of business units and flows with the aim of maximizing global profitability and competitiveness [5, 6].

Many pulp and paper companies are recognizing the potential for supply chain management, and are beginning to develop and invest in their supply chain. Lail [7] identifies some of the main differences that the pulp and paper manufacturing environment has, as compared to discrete batch/repetitive manufacturers.

Study objective
The goal of this study was to elaborate an operations-driven (or “bottom-up”) cost modeling approach which integrates both process and cost information from a pulp and paper mill, and allows representation of process capabilities at the supply chain level for its optimization.

“Bottom-up” approach to supply chain management
For large-scale commodity and capital-intensive process industries like the pulp and paper industry, a tighter integration of operations at the plant level is required in order to fully address the enterprise and supply chain optimization [8]. Process integration, which
consists of the application of methodologies and system-oriented approaches for integrated process design and operation analysis, is concerned with the improvement of the decision-making processes across the supply chain. The aim of process integration is not to focus on a process unit, but rather to integrate the process units, plant, site, and enterprise levels for decision making using a holistic and bottom-up approach that includes the use of process data available in real time, knowledge of manufacturing processes, and process integration tools.

Depending on the time horizon and the importance of the decision that has to be taken, many authors have identified three different SC decision levels, namely the strategic, the tactic and the operational, each of which has a significant impact on the success and profitability of the SC. These SC decision levels, combined with the levels of process control hierarchy, are conceptually represented in Fig. 2. The SC levels usually operate over relatively long time scales (e.g., years for strategic SC decisions), whereas process control activities, such as optimization, control, monitoring, and data acquisition, function at shorter time scales (e.g., seconds for regulatory control), with more frequent decisions affecting the process.

In the process industries, and more specifically in pulp and paper, the SC level decisions tend to be decoupled from activities at the lower levels. Ide-
As illustrated in Fig. 3, the proposed model concept has two important dimensions, namely process and cost. In fact, process and accounting data, generated by the manufacturing processes and the enterprise, are at the basis of the model and are used to analyze process operations and the cost structure at the mill, respectively.

The supply chain, which can be viewed as a number of interrelated systems or business units, can itself be represented as a holistic system having its own rules, i.e. SCM concepts. Using the bottom-up cost modeling approach to represent the SC subsystems, it is possible to incorporate process knowledge within a SC model, so that it can be optimized and used as a decision-support tool, Fig. 4. Therefore, it is possible to ensure consistency across the manufacturing processes, and for large changes in data time scales.

**Process Data Available in Real Time**

The bottom-up cost model concept, as presented above, requires the acquisition, analysis, and use of significant amounts of data, especially process data. However, the challenges related to the data intensiveness of this approach have been facilitated with the advent of information management systems (IMS). Nowadays, real-time process data has become widely available at mills through the implementation of mill-wide data management systems that acquire, store, and manage data [10]. Although most pulp and paper mills have access to significant amounts of data and information from their IMS, they have not fully exploited the data since no systematic and precise modeling has been done in order to turn these data into knowledge for decision making [11]. The most common benefit from IMS is derived from the ad hoc analysis of operations due to increased access to mill-wide data.

Data quality is a critical issue for the bottom-up approach proposed in this study. Therefore, in order to ensure the quality of real-time process data from process data management systems, process data treatment techniques are necessary to ensure the accuracy and precision of measurements. Data processing and reconciliation techniques can be used to correct for various sources of error, including random noise, abnormalities, and inconsistencies, resulting in better quality data for decision making. Furthermore, the systematic application of on-line data processing at near steady-state conditions will enable users to compile data for different process operating regimes, and determine the probability of occurrence of operating parameters [12]. Such information will improve decision support for manufacturing operations management.

**Financial Data and Operations-Driven Costing**

A cost management system implemented at the mill captures enterprise
and financial data, however, they are rarely integrated systematically with process data. Often, cost management is carried out at an aggregated level and the costs are allocated downward to the detailed level, with data distortion occurring as a result. Costing and data consistency can be improved by the bottom-up calculation of costs, similar to process data aggregation [13]. Activity-based costing (ABC) [14] is a cost accounting method based on the principle that resources are consumed by activities that are part of a process necessary to deliver a particular cost object (service or product). Therefore, it is thus possible to monitor how resources relate to activities, which in turn relate to the cost object. Resource and activity drivers respectively determine these relations. In the context of a mill, a similar approach can be used that links resource consumption to production activities at the mill, allowing for the integration of business data and the complexity of the mill operations. Finally, although the consumption of some resources is closely related to the manufacturing operations, other resources are a function of other variables, e.g., the number of changeovers. For this reason, activities are organized following a hierarchy that helps in dealing with the complexity of the mill: unit-level (raw materials, energy), batch-level (changeover, set-up activities), product-level (R&D, marketing), and facility-level (general management activities) [15].

**Case study: high-yield pulp mill**

**Background**

The case study consists of the fibre procurement and production cycles of a high-yield pulp mill. The procurement cycle corresponds to the planning of fibre supply opportunities in order to ensure the fulfillment of fibre requirements at the mill, chip quality, and minimization of the total delivery cost of raw materials. On a shorter-term basis, it also facilitates the management of the procurement network in order to meet inventory targets at the limited on-site and local storage areas, and to ensure logs and wood chips are transported in the right amount and at the right time to the mill. The production cycle consists of first establishing the requirements for each pulp grade, which are a function of both the targeted stock levels and the market pulp demand, and then determining the most profitable production plan for the mill.

In the case study, the mill being considered produces high-yield pulp from hardwood chips using a bleached chemi-thermomechanical pulping (BCTMP) process involving three main production steps: chemical pre-treatment, pressurized refining of fibres, and pulp bleaching. In order to determine the right production plan, three main factors must be considered: inventory level (safety stock, cycle inventory), production costs, and production capability. The production capability refers not only to the throughput of the mill, but also to changeovers between campaigns, the constraints and bottlenecks in the production processes, planned shutdowns for maintenance, unplanned shutdowns due to equipment failure, etc.

Pulp production is a capital-intensive process, and therefore process and capacity utilization is a critical issue. Since material utilization has often been considered to be of secondary importance, large inventories can result. However, due to limited fibre availability, increasing pressure is being placed on fibre procurement activities related to quality, cost, and logistics. There is an opportunity for the optimization of the procurement and production cycles of pulp mills and, given the increasing availability of process information and decision support tools, it is now possible to better represent and reflect the production capability. Although detailed production knowledge should be considered, they introduce additional complexities for the modeling of the supply chain and, depending on the scope of the planning formulation, the resulting models may not be solvable within a reasonable amount of time. For this reason, a bottom-up cost model, describing specific and detailed production processes and operations that reflect the complexities of the manufacturing cycle, will be used as a basis for consistent modeling and optimization between the different levels of logistical management. Depending on the scope of the SC planning question, the mixed integer linear model will incorporate suitable aggregations of inputs from the cost model and, thus, process knowledge included in the SC problem at different aggregation levels will always have a consistent representation, whatever the SC decision level, Fig. 5.
Cost Modeling Methodology

The general steps necessary to build the bottom-up cost model can be divided into the description phase and the investigation phase. As illustrated in Fig. 6, for the first phase, one has to analyse general cost and process information in order to determine which relevant elements should be included in the cost model and, therefore, require a systematic investigation. Then, the systematic investigation involves the acquisition and analysis of detailed process and cost data in order to elaborate the structure of the bottom-up cost model.

Description Phase

The first step of the description phase consists of the development of a holistic understanding of the manufacturing processes of the pulp mill. More specifically, the aim is to determine how process units and activities are linked to the consumption of main resources used in the production process (energy, chemicals, etc.). In order to perform the analysis, three dimensions must be addressed, Fig. 7. First, using available process flow diagrams of the pulp mill, one must determine the process configuration. This mapping step consists mainly of the identification and characterization of machinery used, material flows, and main inputs and outputs of the production processes. Next, it is necessary to determine how the process operates for each grade produced. Usually, recipes available at the mill provide most of the important general information regarding specified production capacity, fibre mix, chemical consumption rate, specific energy of the refiners, consistencies, temperature, quality, etc. Finally, an important step is to capture manufacturing know-how at the pulp mill in order to gain general process knowledge of equipment, production path, and operating conditions. This last step, which consists of discussions with process engineers, superintendents, and the mill manager, allows for the consolidation of general production information concerning both process configuration and operation.

The second step of the description phase consists of the determination and classification of the different resources that have to be considered for the manufacturing of each grade. Using the general ledger, it is possible to differentiate resources and to separate the different aggregated costs that are more related to the enterprise (i.e., general administrative activities sustaining the mill) from those that are related to the production process. Then, within the latter category, one must differentiate further between resources that can be linked directly to the production process (generally using mass and energy balances), and resources related to daily and fixed production costs (e.g., maintenance, supervisory, etc.).

Finally, by examining which resources are linked with costs in the traditional general ledger system and how these resources are linked to the production processes for the production of a specific pulp grade, it is possible to determine the elements that should be considered in the cost model formulation. The production process was subsequently represented by ten cost centres. Eight of these were directly related to the specific activities required to produce different pulp grades: chip pre-treatment process, refiners, screens and cleaners, reject refiner, pulp bleaching, pulp washing and dewatering, dryers and finishing line. The two others, the wastewater treatment process and reboiler, are supporting activities that are closely related to the main process line.
Investigation Phase

The objective of the investigation phase is to determine the process capability and the process-based cost of the production process for each grade. The 10 cost centres and their associated activities are systematically analyzed with respect to the different pulp grades produced. As mentioned previously, process capability refers to the detailed description of how the process is operated for each grade (capacity, flow rate, etc.) and the operations-driven costs are calculated based on the detailed description of the resource drivers.

By consulting the different sources of information about the mill’s processes (P&ID, DCS, PI ProcessBook), the first step consists of determining the necessary data collection points (commonly called PI tags) among the data available in real-time. As an example, for the cost centre (index c) corresponding to the bleaching process, or c=5, as illustrated in Fig. 7, the important process tags (PT, index τ) with respect to the process capability are the consistency and the production rate (PT τ=1, PT τ=2). In respect to the process-based cost, the important resources to consider at this cost centre are the different chemicals used for bleaching (PT τ=3, PT τ=4, PT τ=5, PT τ=6).

For each chosen process tag τ, the available data are downloaded for a given period (for instance, 3 months) and, knowing the historical production plan, it is possible to classify the data per grade and per production run. Using process knowledge, or more sophisticated data treatment tools like wavelet-based data processing and reconciliation techniques, it is necessary to treat the data in order to improve data quality and to obtain the relevant steady-state periods for each grade. Then, by statistical analysis, it is possible to determine the average process value (PV c,τ,g) for each selected data collection point τ, for each grade produced at the mill (index g). As a result, illustrated by Table I for the bleaching process (c=5), the process value matrix obtained represents a “process snapshot” of the operation in the cost centre, for each of the grades produced.

In order to determine the operations-driven cost, the unit costs of the resources used are determined by first examining the available cost information in the accounting system of the mill. The resource drivers are then selected from the process-value matrix.

In the case of the bleaching process, the relevant process values used as resource drivers are PV c,τ,g, (Table I). The costs are then determined by multiplying the corresponding unit costs, CV, in Table II, and resource drivers and this, for each grade produced. This is represented by the following equation, where TR τ,r is the set of association between process tags and resources (index r).

\[ CV_{c,\tau,g} = C_r \cdot \sum_{\tau \in TR_{\tau,r}} PV_{c,\tau,g} \]

The resulting cost value matrix consists of a “cost snapshot” corresponding to the “process snapshot” of the operation in the cost centre, for each of the grades produced, Table III.

As shown in Fig. 8, each process producing a particular grade is split into different activities performed in the ten cost centres. All of these activities are represented, including the specific supporting activities that are not directly related to pulp production, but are closely linked. This bottom-up approach must be performed for all production activities at the mill. The set of process value matrices is used to characterize the process capability, as well as to determine the resource drivers and a set of corresponding cost value matrices. Together, they represent the production process for each of the grades produced and constitute an important part of the operations-driven cost model. In the cost model schematic, this is represented by the process values (PV c,τ,g) and cost values (CV c,τ,r) for each activity performed for a specific grade at a particular cost centre.

Finally, the enterprise-based resources, as well as the production-based resources that only have an implicit relation with the production processes, will be considered in a simpler manner. These costs, related to the enterprise and all ten cost centres, influence the profitability of the mill and therefore must be included in the analysis. They can be treated in an aggregated $/h charge that each
grade will incur when being produced. These are represented by $C_{r\rightarrow SSA_1}$, $C_{r\rightarrow SSA_2}$, ..., $C_{r\rightarrow SSA_8}$ in the case of the production-based resources, and $E_{SA}$ for resources linked to the enterprise supporting activities, Fig. 8.

**Special Case of Grade Changeovers**

Grade changeovers represent an important element in the operation of the mill. These batch-level activities have important associated costs. Three main elements must be taken into account during a changeover period: a) lost opportunity, b) the fixed hourly cost, and c) the cost of the activities performed to produce the mix grade pulp (or grade waste). The importance and impact of these elements are closely related to the total changeover time (in the two first cases) and the total amount and properties of the mix grade pulp (in the latter case). Therefore, the changeover sequence, i.e., the pulp that was produced and the pulp that will be produced, is very important. Moreover, using available production data and process knowledge at the mill, careful analysis of the changeovers must be carried out as precisely as possible in order to determine the relevant characteristics for each changeover possibility (with respect to the changeover time, mixed resources consumption, mix grade pulp produced, technical feasibility, etc.).

The first element, which relates to the lost opportunity of producing and selling pulp during the changeover time, can easily be taken into account by the SC optimization problem. In fact, this will be represented by sequence-dependent transitions and by taking into account the effective production window, which depends on the fixed changeover time (between the pulp produced and the pulp to be produced) and the production flexibility (optimal number of changeovers for a given set of conditions).

The fixed hourly costs (in $/h), which have been established for the production, also need to be taken into account because they are incurred by the cost centres and the enterprise even though a changeover is executed. This places an emphasis on the cost of using “production time” at the mill and on reducing the time required to carry out changeovers. As seen in Fig. 8, these costs are represented by $E_{SA}$ and $C_{r}$ and are the same as during normal production time.

The third main element is the cost of the activities performed in the cost centres to produce the mix grade pulp (or grade change waste). The resources drivers are difficult to identify and their value is somewhere between each of the two grades involved (e.g., $PV_{A-G, s}$, $CV_{A-G, d}$). Clearly, process and cost values will depend on the specification and properties of the two types of pulp involved in the changeover. For instance, a changeover between two grades having different wood species will more likely give rise to big process operation changes and a longer changeover time than a changeover between two grades having different brightness specifications (especially if customer specifications can be overlapped).

Finally, using process analysis and the bottom-up approach, it is possible to provide information for each relevant changeover sequence at the mill and to determine both the total changeover fixed charge and process-related costs. Therefore, these batch-level activities can be included in the SC planning formulation.

**Implications of the bottom-up approach to SCM**

In the pulp and paper industry, with the product price being determined mostly by market conditions, the profitability is strongly influenced by the efficiency of usage of the manufacturing capability and of resources along the entire SC (e.g., raw materials, energy). The bottom-up approach to SCM has the following advantages:

- Compared to more traditional approaches that typically use nominal production rate, the bottom-up cost model framework uses process data available in real-time, allowing a better representation of manufacturing complexity. The treatment and analysis of process data can provide a better characterization of the manufacturing process (constraints, bottlenecks) and therefore a more advanced model for decision-support tools.
- This approach helps to elicit detailed information on operating conditions and resource drivers and, combined with a systematic process-based cost analysis, can provide detailed cost models to determine...
transparent production costs for each grade produced.

• The process view, which considers each activity performed for the production of a particular grade, allows the identification of cause-and-effect relationships (resources drivers) between the consumption of resources, the activities performed, and the particular pulp grade produced.

• The bottom-up approach helps to incorporate important batch-level activities within the production planning, such as changeovers, by careful analysis of process information and existing knowledge in order to determine the cost behaviour.

Finally, the bottom-up framework allows for a detailed view of the activities performed at each cost centre, and gives a structured framework providing the required visibility in the supply chain for shorter-term pulp mill scheduling as well as longer-term fibre procurement planning.

Conclusion

In today's challenging business environment, the availability of both process and cost data has given the pulp and paper industry the opportunity to be able to learn from process and cost history, to analyze their manufacturing processes and their supply chain as a whole, and to create added value accordingly. This paper outlines a methodology for the representation of process complexity and capability within the supply chain context which incorporates value from real-time process data. The cost modeling approach highlights the necessity of adopting a multidisciplinary operations-driven (or bottom-up) approach, integrating both process and cost information from a pulp mill. Finally, a deeper analysis of the data available and the use of consistent cost and process models allow for an increased visibility and understanding of the supply chain, and the development of adequate knowledge for shorter-term (pulp mill scheduling) and longer-term (fibre procurement planning) SC decision support.

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Literature


Résumé: Dû à l’implantation de systèmes de gestion de l’information, les données de procédé et de coûts sont disponibles en quantité pour les compagnies papiéteries. L’analyse systématique de ces données et des procédés de production critiques permet de mieux intégrer la réalité des procédés manufacturiers de l’usine au contexte de la gestion de la chaîne logistique. Cet article présente une approche de modélisation des coûts intégrant des modèles basés sur les données du procédé disponibles en temps réel et les données de comptabilité pour réfléchir aux contraintes liées au procédé de production dans la formulation du problème de la chaîne logistique. La complexité des opérations de l’usine est représentée à l’aide d’une méthode de calcul des coûts basée sur le procédé. Cette dernière démontre comment les ressources sont consommées par les activités effectuées et comment les activités sont reliées aux objets de coûts. Le développement d’un tel modèle d’affaires ascendant, qui servira de support à l’optimisation des cycles d’approvisionnement et de production de l’usine, est illustré pour une usine de pâte à haut rendement. Finale-ment, les implications potentielles de cette approche dans le contexte de l’industrie des pâtes et papiers sont discutées.


Keywords: INFORMATION SYSTEMS, PULP MILLS, SUPPLY CHAIN, OPERATIONS-DRIVEN COST MODELING.

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