

Integration of Planning and Scheduling in Multi-site Plants: Application to Paper Manufacturing

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Abstract

In this paper, a general multi-level decomposition based framework has been proposed for integration of planning and scheduling in a multi-site, multi-product plant, with applications to paper manufacturing. The problem involves complex issues relating to large-scale production in a hybrid flowshop configuration, decisions relating to minimizing trim losses, while maintaining on-time delivery of orders. Due to these complexities, the overall problem of integrated planning and scheduling is logically partitioned into several levels, depending on the problem size. As followed in other decomposition-based approaches, the upper level models are equipped with appropriate abstractions of the lower level constraints. Also from a reactive scheduling point of view, some pro-active measures are embedded into the multi-level structure. The proposed multi-level decomposition scheme is demonstrated on a representative planning and scheduling problem.

Keywords: Planning, Scheduling, Integration, Decomposition

1. Introduction

Integration of planning and scheduling in the process industries has received significant attention in the recent years by practitioners and academicians because of the high economic incentives and the challenges involved. Most of the large-scale multi-enterprise facilities currently employ some heuristics for this integration and are generally dissatisfied with the resulting inconsistencies in decision-making (Shobrys and White, 2000). Over the last few years, though some progress has been made in this direction for development of more superior frameworks for such integration problems, there is a large scope for additional improvements.

In the literature there are several works on planning and scheduling. Shah (1998) gives a detailed review and current status on single and multi-site planning and scheduling. However, there has not been much work done in the literature towards the integration of planning and scheduling in the paper industries. Pinar et al. (2002) proposed an agent

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based decision support system termed as Asynchronous Team (A-Team) framework for central planning and scheduling of gross root paper industries based on heuristics. The challenges are in terms of the complex issues relating to handling large-scale advanced planning and scheduling problems leading to combinatorial explosion of the problem sizes for centralized decision-making. Moreover, the horizons of interest are broadly different in planning and scheduling models. Hence, decomposition based approaches have been increasingly gaining attention in the recent years. Additionally, in the decomposition based approach, the models at the upper levels must reflect accurate abstractions of the lower levels and should be revised as infrequently as possible when compared to the lower levels. The planning models must be consistent with lower level scheduling models, and the scheduling models must again be consistent with the plant level operation thus achieving the vertical integration. Traditionally, the decisions in an enterprise flow in a top-down manner leaving less degree of freedom at lower levels for rescheduling, leading to frequent revision of targets set by the top levels. Embedding contingency measures for integration of rescheduling has been ignored in most of the works published.

With this motivation, in this paper an integrated multi-level decomposition based framework has been proposed for efficient integration of planning and scheduling for a multi-site, multi-product plant with applications to paper manufacturing. Production-planning and scheduling for paper manufacturing in real world environment involves intricate issues related to large-scale production in a hybrid flowshop configuration. Issues related to minimizing trim loss while maintaining on-time delivery of orders need to be addressed. Typical real world problems have about 1000-5000 orders to be manufactured across 5-10 paper machines from 3-6 mills in 1-3 months time (Pinar et al., 2002). The resulting formulation involves solution of mixed integer linear/nonlinear problems with very large number of variables and constraints. Despite the significant progress in the computational resources in the recent years, such large models cannot be solved with the capabilities of the existing solvers. Hence a decomposition based solution approach is necessitated. In this work, we consider a mathematical programming based multi-level framework with minimal heuristics for the above integrated planning and scheduling problem. This is an extension of the earlier work (Munawar et al., 2003; Munawar and Gudi, 2004) but oriented for multi-site plants.

This paper is organized as follows. In the next section, we discuss a general multi-level decomposition based framework. Later in section 3, the proposed framework is illustrated for solving the integrated planning and scheduling problem in a paper manufacturing industry, along with a representative case study.

2. Multi-level Decomposition based Framework

Consider a general multi-site, multi-product planning and scheduling problem with several plants located in different geographic locations with product demands specified over a multi-period operation. Each product has different site dependent manufacturing/production cost, and depending on the customer location there is also an additional transportation cost involved from the manufacturing location. Furthermore, each site has some inventory cost for products produced earlier than their due date, and a tardiness penalty for products produced later than their corresponding due date. At

each site, a generic hybrid flowshop configuration of various machines is assumed that can be easily simplified to any problem specific topology of series and/or parallel configuration of different stages.

The global objectives are minimizing the overall costs discussed above and timely satisfaction of customer orders with minimal impact of the disruptions if any (machine breakdowns etc.), on the plant operation. The latter objective is achieved implicitly through the proposed proactive measures for local attenuation of the plant disruptions leading to infrequent revision of the commitments made to the customers. Based on the inherent, functional decomposition of the global objectives, the overall problem can be traditionally decomposed into two major levels, a primary level for strategic (or long-term) planning over a multi-period operation across multiple sites and a secondary level for tactical (or mid-term) planning and scheduling at each site in each time period.

The primary level has multi-period demands over a longer horizon (say 1 year) and has an abstraction of each plant in terms of the average production and inventory capacities. Accordingly, based on minimization of the overall cost mentioned above, the abstract model at this level sets production targets for each plant. Additionally at this level we consider an abstraction of the other production losses that may possibly occur at the lower levels. The production losses could be either the trimming losses in cutting stock problems or the slopping losses during grade changeovers in refinery problems (Munawar and Gudi, 2004). The primary level is revised on a less frequent basis (say monthly/quarterly) to avoid frequent revision of the commitments made to customers.

At the secondary level, for mid-term planning and scheduling at each site/plant with detailed plant constraints, the horizon of interest is smaller (1-3 months) catering to less number of customers, and the model here may be revised/updated on a frequent (say weekly/monthly) basis but without violating the global objectives. The lower levels have detailed constraints to account for the production losses mentioned above. Depending on the complexity of the problem these levels may further need to be decomposed as discussed later in section 3.2. From a reactive scheduling point of view, some pro-active measures are embedded into the multi-level structure; such as assuming higher production losses at the top levels; and appropriate relative penalties to some of the cost terms in the objective function. This is motivated towards better flexibility at later stages for reacting to unforeseen plant disruptions.

3. Application to Paper Manufacturing

The major decisions in paper manufacturing are order allocation across multiple sites, run formation and order sequencing in each paper machine, trim schedule for minimum wastage of paper and a load schedule for order distribution to various destinations. In this work, we consider decision support for only the first three processes and propose ways of solving the integrated production planning and scheduling problem.

3.1 Paper Manufacturing as a Hybrid Flowshop Facility

The superstructure of all the alternate production routes for producing different paper products at any site can be viewed as a hybrid flowshop facility. For a site with two paper machines for producing different grades of paper, the paper machine operates in a disjunctive mode; i.e. only one paper grade can be produced at a time, and involves

transition time for grade changeovers which might be sequence and machine dependent. Orders of smaller roll dimensions may often need to be further cut on common rewinders (parallel lines) before they are wrapped and packaged for dispatch.

3.2 Multi-level Decomposition

The proposed multi-level framework is shown in Figure 1. For small-size problems with fewer customer orders, a two-level decomposition may be adequate as shown in Figure 1(a), while for medium to large-scale problems a four level decomposition, as shown in Figure 1(b), is found to be necessary for obtaining the solution in real time.

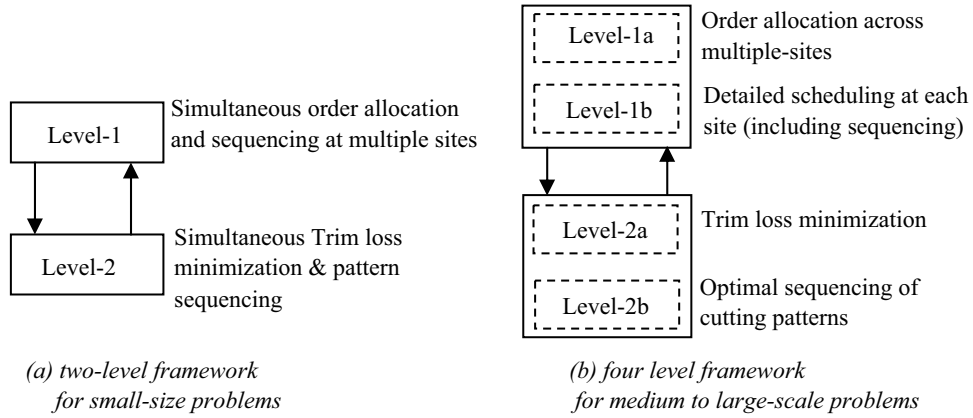


Figure 1. Proposed multi-level framework for multi-site paper manufacturing

In Level-1 problem of Figure 1(a), a MINLP formulation has been proposed for simultaneous order allocation and grade sequencing across multiple sites with assumed trim losses, which is later linearized to an MILP after removing the bilinearities. For addressing the complex issues related to large-scale production in a hybrid flowshop configuration at the upper levels, some simplifying assumptions have been made. Generally the production rates in a paper machine are much lower compared to processing in other downstream units. Hence, the order allocation problem is generally assumed to be based on the aggregate properties of the paper machine alone rather than based on the entire production route in the hybrid flowshop. For medium to large-size problems as shown in Figure 1(b), the objective at the top sub-level (Level-1a) is primarily order allocation (without sequencing) across multiple sites with assumed production losses; while at the next sub-level (Level-1b) the objective is sequencing of grades for each paper machine individually, with penalties for violation of due dates. Before going into the details of the lower level problem (Level-2) we first present the results of the upper levels for a representative problem.

Case Study on Small-size Planning and Scheduling Problem: Consider 4 paper machines at 3 paper mills located in distinct locations for meeting 21 orders placed from 5 different customers. All the MILP models in this work are solved using CPLEX solver on ILOG OPL STUDIO, while the MINLP model is solved using SBB solver on GAMS. When we applied the simple two-level decomposition shown in Figure 1(a), the MINLP problem at Level-1 takes long computational time (more than 1 hr). When the four-level decomposition shown in Figure 1(b) was applied, both the sublevels at Level-

1 together are solved relatively faster to find the order-machine allocation and grade sequencing (for all 4 machines).

On each paper machine, for the set of orders assigned to each time slot, the problem at Level-2 involves trim loss minimization and sequencing of optimal cutting patterns. In the literature, typically, the trim loss problems (Level-2a) and the sequencing of the optimal cutting patterns (Level-2b) are solved sequentially (Westerlund et al., 1998; Westerlund and Isaksson, 1998). Due to the current computational limitations, the traditional sequential approach (Level-2a followed by Level-2b) needs to be used for large-scale problems. In this work, it is demonstrated that for small to medium-size problems, the proposed novel approach (aggregate Level-2) shown in Figure 1(a) for simultaneous trim loss minimization and sequencing of cutting patterns has more flexibility leading to better customer satisfaction and lower overall costs.

3.3 Simultaneous Trim loss Minimization and Sequencing of Optimal Cutting Patterns

Consider the one-dimensional trim loss problem with fixed deckle size of the paper machine that allows variation only in the length of the cutting patterns. Given the problem parameters of the paper machine and winder, along with the data related to the customer orders, the total number of feasible cutting patterns can be enumerated using the explicit procedure listed in Westurlund et al. (1998). The link between the trim loss minimization problem and the pattern sequencing problem is through the use of the common decision variables for selection of optimal patterns and their corresponding optimal lengths. The resulting MILP problem formulation is not presented here due to space limitations. We assume as many time slots as the total number of feasible cutting patterns. Since all the cutting patterns may not be selected at the optimal solution some slots would be empty. (When the number of feasible cutting patterns is large it may lead to combinatorial problems and hence the proposed simultaneous approach is applicable to small to medium size problems, otherwise the sequential approach is recommended). We enforce unique allotment of a pattern to a time slot with the provision for some slots being empty. All the empty slots are pulled towards the beginning of the horizon and the corresponding decision variables are assigned to zero for these slots. The objective function includes penalties for tardiness and under production, in addition to the costs resulting from trim loss and knife changes (due to the transition between patterns).

Case Study: For illustrating the proposed model, consider a set of 7 orders of the same grade assigned to a single slot. For the given problem data, the total number of feasible patterns are enumerated to be 22. Using the trim minimization problem, 7 optimal set of patterns are selected (p5, p9, p14, p17, p18, p19 and p22) and the total cost is \$20504. Then the pattern sequencing problem for these 7 optimal patterns yields a total tardiness cost of \$2438. The overall results for the traditional sequential approach are:

% Trim loss	: 1.0312
Trim cost	: \$9899
Under production cost	: \$9906
Knife change cost	: \$700
Tardiness cost	: \$2438
The total cost	: \$22943
The optimal sequence is: p17 → p9 → p5 → p18 → p19 → p22 → p14	

When we solve the proposed simultaneous trim minimization problem and pattern sequencing problem, the following output is obtained. 10 optimal patterns are selected.

% Trim loss	: 1.0313
Trim cost	: \$9901
Under production cost	: \$9907
Knife change cost	: \$1000
Tardiness cost	: \$1015
The total cost	: \$21823

The optimal sequence is: p17→ p12 → p9 → p5 → p21→ p19 → p22→ p18→ p14 → p7

A comparison of the above results reveals that, though there is an increase in the knife change cost for the 10 optimal patterns selected by the simultaneous approach, there is a drastic reduction in the tardiness costs for the same trim loss and underproduction costs and hence the overall costs for the simultaneous approach are relatively lower.

Conclusions

In this paper, the integration of planning and scheduling in a multi-site, multi-product plant is discussed with applications to paper manufacturing. At the lower level a novel simultaneous approach is proposed for the combined trim loss minimization and pattern sequencing problem. Realistically (large) sized industrial problems would bring in further complexities (constraints) and challenges that require novel approaches for decomposition and global solution; this is an aspect of future research.

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