A MULTI-LEVEL, CONTROL-THEORETIC APPROACH TO REACTIVE SCHEDULING IN CONTINUOUS PLANTS

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Abstract

The paper presents a receding horizon based approach to reactive scheduling of continuous plants. The proposed approach is based on the inherent, functional decomposition of the overall scheduling task in terms of short and long term operating objectives. The multi-level, control theoretic approach proposed here is shown to naturally result from this functional decomposition. An illustrative case study of a simple refinery flowsheet involving scheduling in a hybrid flowshop is presented here to demonstrate the proposed methodology.

Keywords

Reactive scheduling, Multi-level, Control-theoretic, Receding horizon

Introduction

One of the key aspects of optimal operation, especially in the context of refinery planning and management, is the deployment of efficient and robust task schedules. These schedules need to be designed based on short term as well as long-term operating and business goals. Achievement of short-term goals help to minimize the delay and production cost in fulfilling orders and maximize the total production value. Long term scheduling is useful in determining the timing of the operating campaigns and in determining the optimal use of available equipment towards maximizing productivity.

Often times, schedules derived based on known parameters (such as demands, due dates) and theoretical considerations (mass balance, yields), need to be continuously evaluated to ensure that they do not violate critical operating constraints/ goals. Other decision parameters such as process yields, processing times/ rates, material arrival/ lifting times and even production targets themselves could change, after the nominal schedule is deployed. Furthermore, in the dynamic environment of processing operations, unexpected events continually occur and cause deviations from the expected production targets. Broadly, the two approaches that have been proposed in the literature, to react to such uncertainties and variations, focus on either (i) complete re-evaluation of the nominal schedule under the changed conditions, or (ii) partial revision or 'repair' of the nominal schedule to accommodate the deviations. The approach proposed in

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this paper is closer to the latter approach of reactive scheduling so as to maintain optimal operation in the presence of the parameter uncertainties/ variations.

In process scheduling literature, most of the approaches to reactive scheduling have been focused on batch plants. Aspects related to robustness of schedules, in the presence of uncertainties, was studied by Mignon et al. (1995). Rodrigues et al. (1996) proposed a reactive scheduling technique based on State Task Network (STN) formulation of the scheduling problem that also incorporated a rolling horizon based representation to simplify the problem. Sanmarti et al. (1996) proposed a combined robust/ reactive scheduling approach to batch processes in the presence of task processing time variations. Recently, Henning and Cerda (2000) proposed a framework for knowledge based predictive reactive scheduling that incorporates knowledge of the human experts with automated scheduler capabilities. Sun and Xue (2001) propose a dynamic reactive scheduling approach for modifying nominal schedules that could not be completed due to changes in the production target or manufacturing resources.

This paper proposes a control theoretic approach to reactive scheduling with a focus on continuous, multi-product, multi-stage plant scheduling. The approach proposed here is based on two key characteristics of the scheduling problem that project a potential for problem simplification. The first is that, like in process control tasks, there is a natural, temporal decomposition of decision making in a typical plant shop floor. Hierarchically, the upper layers focus on long-tem objectives of profit and demand satisfaction while the lower layers look at relatively shorter term objectives of target satisfaction in the presence of shortfall transients. The second important characteristic is that the typical constraints at the lower hierarchical plant-floor levels are relatively short-term, flexible and potentially relaxable human constraints. This offers a potential for decomposition and heuristic problem solving at the lower levels. In our work, these characteristics have been exploited toward developing a framework that simplifies the reactive scheduling problem. The proposed framework also uses the receding horizon formulation, which has been so elegantly exploited in advanced process control algorithms, with real time feedback of production shortfalls, to ensure optimal satisfaction of the production targets. The multi-level solution approach is described next.

Multi-level Formulation

The motivation for the multi-level structure of the scheduler stems from the hierarchical nature of information flow that is typically seen in a refinery production environment (Figure 1). Typically at the *corporate level*, the horizon of planning is fairly extended and is based on actual (known) and forecasted demands. Functionally, the corporate level is minimally concerned with reacting to short term production transients; rather the mandate at this level is to react to long term slack or short fall that is available through feedback from the *supervisory level* (see Figure 1). The objectives here are in terms of determining production targets with a view to maximizing profits. The production targets are passed on to the supervisory levels whose objective is typically to ensure that these targets are met keeping in mind the actual production level constraints. The horizon of focus at this level is relatively short term; in terms of its role in reacting to short term transients, this layer could have a greater degree of involvement in decision-making.

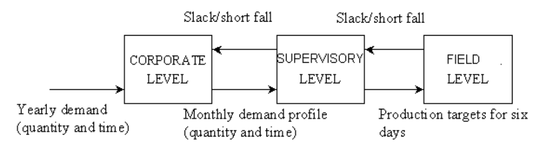

Figure 1. Information flow in a production environment

At the lower *field level*, the production targets are imposed over much shorter horizons by the supervisory layer. Expectedly, this layer would play a dominant role in reacting to short term disturbances. The objectives at the lower layers would be predominantly on meeting the production targets imposed by the supervisory layer.

In terms of nature of the constraints posed at each of the layers, the upper layers would be characterized by hard and relatively rigid constraints; for example, the inventory constraints or its abstractions at the upper layers need to be accommodated in the resulting schedule. However, at the field level, the constraints are relatively flexible and potentially relaxable; for example, the temporary non-availability of a particular storage inventory can be accommodated at the field level, by an appropriate inventory management policy developed using operating heuristics. As seen in Figure 1, a feedback mechanism from the lower levels apprises the upper layers of the individual performance metrics so as to enable appropriate corrective planning at the upper layers.

In the present work, we restrict the decomposition of the overall problem involving multiple due dates, to two levels. The third level of decomposition, incorporating operating heuristics and inventory management policies, is currently under development. Figure 2 shows the schematic decomposition at the two levels. The model formulation at Level 2 includes a receding horizon window, which represents the time over which demands are considered. Thus, at any instant within the first due date, the total demands at Level 2 will include the unsatisfied demands (foreseen and unforeseen, including those updated by real time feedback) within the first due date as well as some projected demands from the second due date as well. The model formulation at Level 1 considers all demands up to the last known due date whereas Level 2 focuses on meeting the demands of the first known due date. As stated earlier, the model formulation at either of the levels would include the mass and inventory balances and constraints related to the sequence of processing and transitions. To simplify the model formulation at Level 1, the inventory constraints are abstracted in terms of equivalent bounds on the processing times in each stage. These bounds can be calculated conservatively from knowledge of the processing rates and the inventory volumes. Thus, the schedule generated at Level 1 predicts targets that could be realistically imposed on Level 2. The formulation at Level 2 includes detailed inventory constraints (including breakpoints) and mass balance constraints. For brevity, the detailed model equations at each of the levels are not being presented here but can be found in Munawar et al. (2002).

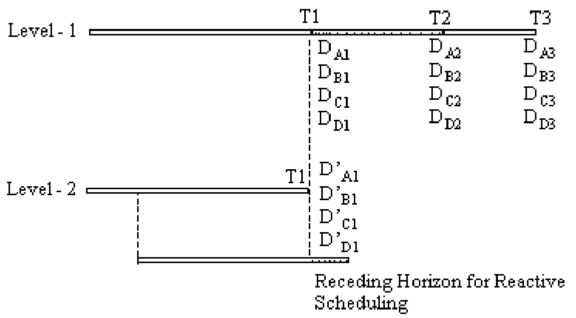

Figure 2. Proposed multi-level framework with receding horizon for reactive scheduling

The framework proposed here is in line with cascade control structure that is used in process control practice. Local disturbances / production shortfalls or transients are attenuated locally before they affect the global performance of the loop/ schedule. Also, the design of the outer loop (Level-1) controller (optimizer) does reflect the inherent characteristics of the inner loop (Level-2); for example, bounds on the processing times at Level-1 reflect the inventory constraints at Level-2. Also, the receding horizon strategy accommodates production shortfalls locally as much as possible failing which it enables optimal extension of the due dates so as to meet the production targets.

For short term scheduling of multi-product, continuous plants involving a single due date, Pinto and Grossman (1994) presented an MINLP formulation involving mass and inventory balance constraints in addition to the constraints on processing sequence and transitions. To solve the resultant problem, they also presented an elegant solution methodology based on the Generalized Benders Decomposition and Outer Approximation. However, when demands at multiple due dates are posed as indicated earlier, the MINLP model formulation and solution to obtain the nominal schedule could become quite complex. Furthermore, re-establishing an optimal schedule, in the presence of unforeseen disturbances/ shutdowns at the plant floor, could be computationally quite prohibitive. The proposed multi-level framework could address the above problems and aid in regeneration of the schedules. The proposed methodology has been validated on a representative refinery-scheduling problem involving a multi-product, multi-stage continuous plant operating in a hybrid flowshop facility.

Problem Definition

A flow diagram of the hybrid flowshop facility involving 4 products and 3 stages is shown in Figure 3. In this flow diagram, Line 1 and Line 2 relate to the same processing task (for e.g. extraction); however Line 2 is an additional parallel unit that is present to accommodate increased demands on certain products.

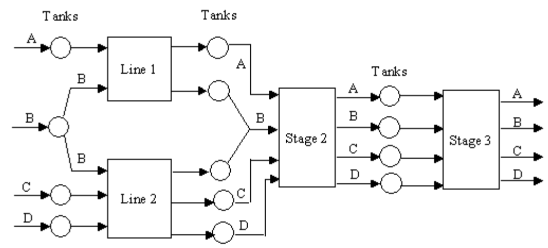

Figure 3. Flow diagram of the hybrid flowshop facility

With the exception of component B, which can be processed in both the lines, all the products have to be processed one at a time in all the stages in the same sequence: Line1 or Line2 followed by Stages 2 and 3. The feed rates of components A, B, C and D are assumed to be constant: 21, 28, 17 and 16 m^3/hr. The transition between one intermediate grade to the next involves a transition period during which a slop stream is generated. The yields, the lower and upper bounds on processing rates and the transition time data are given in Table 1.

Table 1. Data for yields, processing rates and transition times

Yields

Grade	Line1	Line2	Stage2	Stage3
A	0.73		0.73	0.91
B	0.69	0.51	0.67	0.95
C		0.48	0.48	0.98
D		0.48	0.48	0.98

Lower and upper bounds on Processing rates (m^3/hr)

Grade	Line1	Line2	Stage2	Stage3
A	25 – 60		30 – 72	23 – 57
B	27 – 60	35 – 70	28 – 70	20 – 55
C		36 – 70	26 – 72	23 – 58
D		40 – 65	28 – 70	20 – 55

Transition times (hr)

Grade	Line1		Line2			Stages 2 & 3			
	A	B	B	C	D	A	B	C	D
A	0	1				0	1	4	4
B	1	0	0	3	3	1	0	3	3
C			3	0	0	4	3	0	0
D			3	0	0	4	3	0	0

All the inventories are assumed to be of 1000 m^3 capacity. The presence of finite inventories for the intermediates between the lines and individual stages requires the operation to be cyclic; the feed side inventories place bounds on the cycle time for processing of all the products once through all the stages. Demands for the finished products are specified at various (multiple) due dates over a horizon as seen in Table 2.

Three due dates are considered at Level-1, each of 1000, 900 and 800 hrs duration respectively. The upper bound on processing times on all products is specified as 50 hrs at Level-1 to reflect the inventories to be handled at Level-2. Thus, for multiple due dates' case, it is evident that an effective scheduler would have to distribute the processing tasks so as to be optimal with respect to all the due dates. For example, a high demand for a particular product at the second due date would require the processing to be distributed over the entire time up to the second due date, even though the demand for the product at the first due date is low. Even otherwise, the scheduler must push in tighter schedules in the early due dates so that there is some levy in the forthcoming due dates to accommodate the unforeseen events.

Table 2. Comparison of demands specified and that of projected by Level-1

Specified Demands (m^3) at each due date

Grade	Due date1	Due date 2	Due date 3
A	5237	4713	4190
B	8414	7572	6731
C	975	878	780
D	975	878	780

Demands (m^3) projected by Level-1

Grade	Due date1	Due date 2	Due date 3
A	5642.2	4941.3	3556.5
B	8414.0	7572.0	6731.0
C	1294.8	1338.3	0.0
D	1190.6	881.4	561.0

As can be seen from Table 2, for product C in the third due date, the Level-1 scheduler has predicted a zero demand since all of its demand is accommodated by the second due date itself.

For the first due date of 1000hrs, the Gantt chart of the nominal schedule predicted by Level-2 is given in Figure 4.

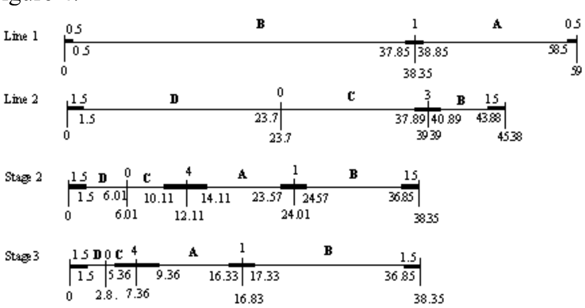

Figure 4. Gantt chart of the nominal schedule at Level-2 for the first due date of 1000 hrs

All the bulk demands predicted by Level-1 are met at Level-2 also with the inventory constraints. The cycle time is 59 hrs. In order to simulate the unforeseen breakdown of units, a shut down time is introduced at the end of ten cycles (590 hrs). The shut down times are varied from 0 to 200 hrs. The current levels of inventory at the end of 590 hrs and the processing sequence are fixed as that of the nominal schedule. The objective function at Level-2 for reactive scheduling, is posed as minimization of the amount of time required to be intruded into the next due date in order to meet the overall demand (slack in the previous due date + demands in the current due date) at end of the receding horizon window. It is observed that at the end of 590 hrs, a maximum shut down time of 53 hrs is allowed for the demands to be met at due date 1 itself, without intruding into the next due date. Then the shut down times are gradually increased. For shut down times of 58, 59, 60, 70, 90 and 100 hrs, the receding horizon approach predicted that we need to go into 2, 9.1, 12.4, 82.7, 231.9 and 295.8 hours of the second due date respectively. For a shut down time of 150 hrs it predicted 680.5 hrs of intrusion into the second due date. But for a shut down time of 200 hrs, even if all of the second due date is included in the receding horizon the bulk demands could not be met. So, for shut down times more than 200 hrs of the problem considered, either the third due date also has to be included in the receding horizon or the slack at the end of second due date can be fed back to Leve-1 for effective redistribution of demands.

Conclusions

A multi-level framework to realistically address reactive scheduling problems has been proposed and has been successfully evaluated on a continuous multi-product refinery plant

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