European Symposium on Computer Aided Process Engineering – 15
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Proactive approach to address robust batch process scheduling under short-term uncertainties

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Abstract

A contribution is made in the area of proactive scheduling with the aim to properly define the scheduling problem explicitly incorporating the effects of short-term uncertainties. The idea is to identify a robust initial schedule with the flexibility to react to unexpected events with minimum effects. The problem is modelled using a stochastic optimization approach where not only a set of anticipated scenarios can be considered, but also the capability to react to events once they occur. A stochastic genetic algorithm is developed to efficiently identify robust schedules with minimum expectance for the wait times and idle times that commonly arise in the operation of batch processes with variable operation times and machine breakdowns. The application of the proposed modelling framework to different batch processes shows the flexibility of the identified initial schedule and highlights the importance of exploiting the information of the uncertainty at the decision stage.

Keywords: Proactive schedule, rescheduling, robustness, uncertainty.

1. Introduction

Process variations and incomplete information are inherent characteristics of any process system, and flexibility to respond quickly and effectively to the dynamic and uncertain environment has become an essential feature for effective scheduling.

Research in scheduling under uncertainty has mostly been focused either on reactive scheduling algorithms, implemented according to the actual situation of the plant once the uncertainty is realized or unexpected events occur, or on proactive scheduling approaches, which tend to generate schedules that are in some sense robust or insensitive to a priori anticipated uncertainties. The execution of optimal schedules based on nominal parameter values and the implementation of rescheduling strategies to face disruptions could result cumbersome and might lead to inefficient or costly reconfigurations as well as to plant nervousness. On the other hand, a robust schedule exhibits an optimum expected performance, but it is not likely to be the optimum one for the actual scenario that will finally occur. Both methodologies have usually been implemented independently, and relatively little attention has been given to the consideration of short-term uncertainties proactively (O'donovan et al., 1999; Kim and Diwekar, 2002; Jensen, 2003).

The incorporation of rescheduling aspects at the time of scheduling is proposed in this work. The identification of a robust initial schedule with the flexibility to react to unexpected events with minimum effects is pursued by explicitly addressing the major effects of variable processing times and equipment breakdowns in short-term scheduling of batch processes.

These effects can be characterized by their main consequences in terms of task scheduling. On one hand, if a breakdown occurs and/or the actual processing time of a task is longer than the scheduled one, the time spent by batches waiting for the availability of the next unit increases. This might lead to unexpected delays, and eventually result in quality problems for sensitive or unstable materials that force the rejection of batches with the consequent increase of operational costs. On the other hand, if processing times are shorter than the scheduled ones, idle times appear and subsequent equipment under-utilization occurs (Figure 1).

The approaches proposed so far that recognize the importance of considering the uncertainty into the decision level do not explicitly address not even analyze these critical situations that can arise during the execution of the schedule. However, the knowledge of this uncertainty can be usefully incorporated at the time of scheduling to reduce the gap between theory and practice, thus reducing reschedule requirements and improving the overall plant performance avoiding the occurrence of the full force of a perturbation. It is highly desirable to balance the trade offs between robustness, rescheduling and performance, and develop an initial schedule able to absorb anticipated disruptions, thus minimizing their effect on planned activities while maintaining acceptable plant performance.

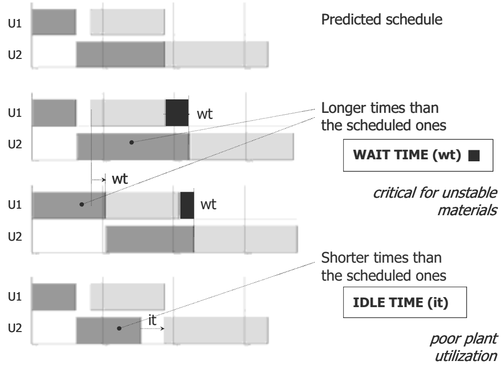


Figure 1. Effects of processing times variability.

2. Problem statement

The scheduling problem addressed comprises a multistage batch plant with a set of orders to be fulfilled, the set of processing stages required by each order, a set of units where they can be processed, the operations required by each stage, and the processing times of each operation, represented by probability distributions. This information has been modelled using the Process-Stage-Operation hierarchical approach defined by the standard ISA-S88 (ANSI/ISA, 1995), which provides a standard terminology and hierarchical structured models for batch processes.

Due to the uncertainty in the operation times a detailed schedule is not pursued, but only the minimum information to be released to the batch process control is established. This information is related to the production sequence, the assignment of units to stages and the initial (expected) processing time of each process. The effects that may arise due to the uncertainty are explicitly managed by minimizing a weighted combination of the expected makespan and the expected wait times resulting from the execution of the schedule under a set of anticipated scenarios. The following assumptions are made:

- From the schedule, the *control level* (ISA S88) requires only information related to the sequence, the assignment of units to stages and the processes start times. Then production proceeds according to the *control recipe*.
- The Non-Intermediate Storage policy (NIS) between stages is assumed.
- Within each stage, all the operations must be executed without interruption. When at the end of a stage (or before a transfer operation) the next unit is not available, a wait time has to be introduced. On the other hand, if a unit is available before the time it is required by the next stage, an idle time appears.

Uncertainty associated with operation times can be represented indistinctly by discrete or continuous probability distributions. The scenario-based representation of the uncertainty is then adopted by sampling over all the probability space to approximate the expectation of the objective function. Other sources of short-term uncertainties can be easily incorporated within the proposed framework at the expense of a larger number of scenarios required to represent significantly all the uncertain space.

3. Modelling

The integrated framework for planning and scheduling of batch chemical plants developed by Cantón (2003) is used in this work for the modelling of the system. A set of tools, integrating both heuristic rules and optimization algorithms, are available to establish the number of batches to be performed, the sequence, and the assignment of production stages to specific units. Based on the characteristics of the problem and the specified objective function, different strategies combining these tools can be used.

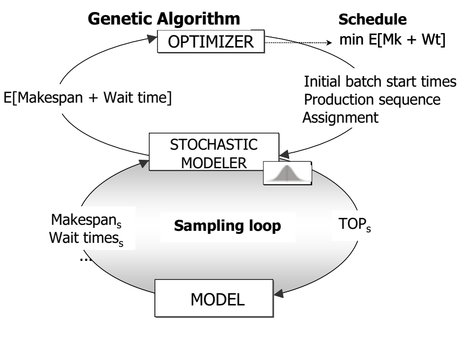


Figure 2. Stochastic optimization framework.

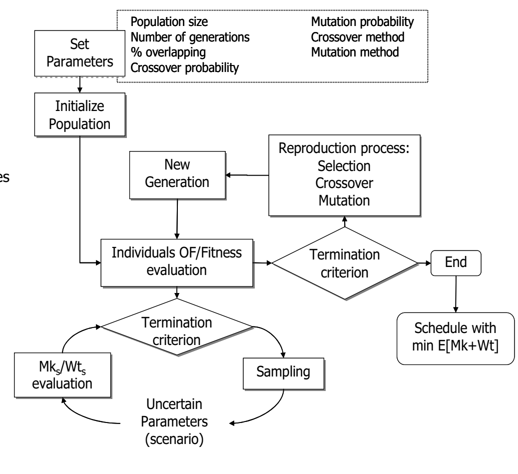


Figure 3. stochGA solution procedure.

A stochastic genetic algorithm (stochGA) has been designed and implemented within this scheduling framework. The GAlib C++ library (Wall, 1996) has been used with customised genome classes. Each individual of the population identifies an initial schedule, and is encoded using a mixed representation involving a real-valued string for the initial batch times, a permutation representation for the sequencing decisions, and a string of integer values for the assignment. For the reproduction process, suitable operators have been implemented in each part of the solution vector.

The developed stochGA involves two recursive loops (Figure 2), and the algorithm proceeds as represented in Figure 3. There is an outer optimization loop controlled by the genetic algorithm, which directs the search to the identification of the initial times of each batch, the sequence and the assignment decisions that minimize a weighted combination of expected makespan and wait times, thus introducing robustness features as pointed out before. This outer procedure incorporates an inner sampling loop within which a set of probable scenarios are anticipated by sampling over the probability space to evaluate the probabilistic fitness for each individual. Specifically, the expected performance of each individual (schedule) is evaluated by computing for each scenario the wait time and makespan values that would occur when implementing its sequence, assignment and initial times under the assumed rescheduling policy; that is, the capability to react to events once they occur is considered when evaluating the individuals. The number of scenarios required to obtain a given accuracy for the actual mean and standard deviation of the performance measure is assessed.

4. Results

The proposed methodology has been applied to a case study based on a process plant involving 3 production stages and 8 operations. A scheme of the process is shown in Figure 4. Uncertainty in the operations of loading, heating and discharging has been introduced and characterized with a uniform distribution function. Two different products can be produced and five orders have been considered for scheduling.

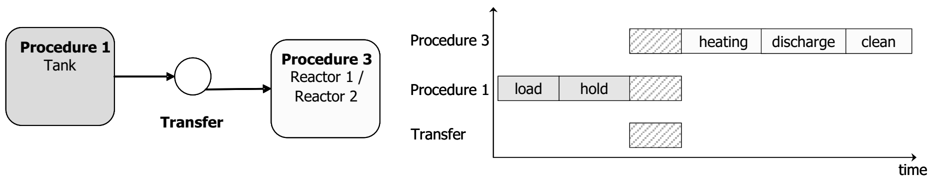


Figure 4. Case study.

The scheduling problem was solved using the proposed stochastic modelling and assuming a right-shifting rescheduling strategy. For comparison purposes, the deterministic problem considering only one scenario with nominal operation times was next solved. The production sequence, the assignment and the processes start times thus obtained were fixed, and the makespan and wait time values that would arise after the occurrence of each particular scenario were computed. The results obtained are summarized in Table 1. Figures 5 and 6 depict the schedules that would be executed in the plant for the nominal scenario and for one of the randomly-generated scenarios, respectively.

Table 1. Production sequence, initial batch times, expected makespan and wait time, and makespan and wait times in the nominal scenario (Mk_{nom}, Wt_{nom}), for the deterministic and stochastic optimized schedules.

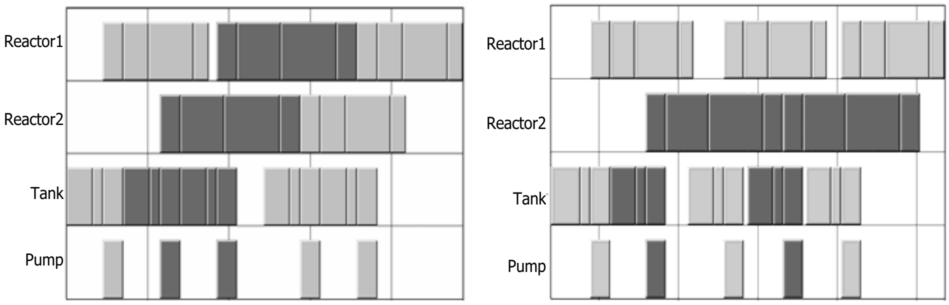
Batch	Deterministic Product	Deterministic Tin	Stochastic Product	Stochastic Tin
1	A	0.0	A	0.0
2	B	5.6	B	5.8
3	B	11.2	A	13.8
4	A	19.4	B	19.8
5	A	25.3	A	25.6
E[Mk+Wt]	40.6		39.8	
$Mk_{nominal}$	39.0		39.7	
$Wt_{nominal}$	0.0		0.0	

From these results it can be observed that the deterministic modelling overestimates the system performance. Although the makespan and wait time values of the deterministic schedule are optimal in the nominal scenario, when the schedule is used to face the uncertainty the expected makespan and wait time value raises about 4%. The schedule identified with the stochastic approach shows a better expected performance over the anticipated scenarios of processing times.

Despite the simplicity of the analyzed case study, and the relatively small variability associated with the uncertain operations, it is important to notice the consequences of neglecting the known uncertainty and the quick loose of optimality when implementing a deterministic schedule.

Concerning the rescheduling features, different policies can be followed when the uncertainty is revealed or unexpected events occur besides avoiding changes once the execution of a schedule has already started:

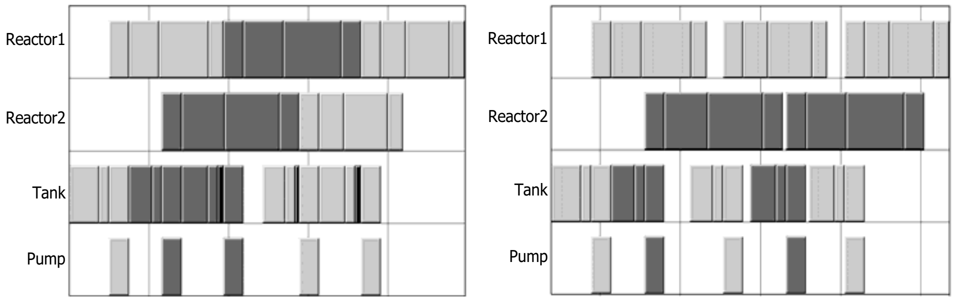
- resolution of the new scheduling problem from scratch,
- right-shifting, generating the new schedule from the initial one just delaying the operations affected by the event,
- more sophisticated rescheduling methods.



(a) Makespan: 39; wait time: 0 (b) Makespan: 39.7; wait time: 0

Figure 5. Schedules that would be executed if the nominal scenario finally occurred according to (a) the deterministic and (b) the stochastic optimization approaches.

Particularly, it can be considered that once a breakdown or an unreasonable wait time is detected, tasks can be just right-shifted or reassigned to alternative units, batches can be immediately rejected and new ones ordered, thus avoiding unnecessary wait times. In such a case, this knowledge related to the rescheduling policy should be incorporated proactively at the time of scheduling to improve flexibility and plant performance.



(a) Makespan: 39.7; wait time: 1 (b) Makespan: 39.7; wait time: 0

Figure 6. Schedules that would be executed in a particular scenario according to (a) the deterministic and (b) the stochastic optimization approaches.

5. Conclusions

A stochastic modelling and optimization approach is proposed in this work to address the processing times uncertainty arising in scheduling of batch processes. A robust initial schedule is identified which shows reduced expected wait times and acceptable line occupation, thus reducing eventual quality problems or unexpected delays.

The applicability of the proposed framework highlights the importance of exploiting the information of the uncertainty at the decision stage by incorporating not only anticipated scenarios but also suitable reactions to improve the flexibility and the final quality of the schedule's overall performance.

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Acknowledgements

Financial support received from the spanish Ministerio de Educación, Cultura y Deporte (FPU research grant to A. B.) and Ministerio de Ciencia y Tecnología (project DPI2002-00856); from the Generalitat de Catalunya (project I0353); and from the European Community (contracts GIRD-CT-2000-00318 and MRTN-CT-2004-512233) is fully appreciated.