An Algorithm for Reactive Batch Sequencing

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Abstract

The specifics of process manufacturing have a great influence on a production management and the focus of production scheduling is to maintain stable production within given constraints. The paper presents a dedicated on-line algorithm that has been developed with the intention of predicting the adequate starting time for a single new batch in a system consisting of two chemical reactors sharing a common discharge vessel. The validation of the achieved results, derived from the algorithm testing, shows that the proposed algorithm can significantly contribute to more stable production and can efficiently deal with the no-wait constraints and the non-uniformity of batch durations of the real case study process.

1. Introduction

Sequencing and scheduling are forms of decision-making that play an essential role in process manufacturing. Over the last three decades numerous approaches to the use of scheduling principles and methodologies in automatic control of industrial processes have been tried. Despite this, production scheduling often remains a manual process performed by experienced and skilled operators. One reason for this is the fact that real industrial processes are much more complex than models treated in academic research (Pinedo, 1995; Dilworth, 1996). In practice, there are many examples of industrial settings in which resource constraints exist, and there may be limits on the amount of time that a job can spend in a buffer between two consecutive operations. Often there is no intermediate buffer between two processing units and a blocking can occur. Sometimes the nature of a technological process itself demands that there should be no slack time between two subsequent operations and no-wait constraints should be taken into account. Until now, the literature has paid surprisingly little attention to flow shop production with blocking, no-wait constraints and uncertainty in the duration of a product cycle. Even less is known about how a scheduling algorithm should respond to deviations in production process, where the response should be on-line and should provide a feasible solution according to the actual situation on the factory floor. Mathematical based algorithms of such scheduling problems seem to be inappropriate for on-line usage (Raaymakers and Hoogeveen, 2000; Pinedo, 1995) due to NP-hardness. On the other hand, the expectations and needs of industrial partners are high, as the trend towards fully automated industrial production systems requires the efficient substitution of experienced operators.

The article is organised into three sections. The first part addresses some features of process manufacturing and their influence on production scheduling. The main part analyses the scheduling problem in a case study subprocess of two-stage gel washing and introduces a simple and reliable algorithm to avoid typical problems concerning shared resources and non uniform batch durations. The third part describes testing and evaluation of the proposed algorithm and the results achieved.

2. Scheduling in process industries

One of the main activities within a production management level is production scheduling. The process industry has several specifics compared with the discrete industry (Thomas and Lamouri, 1998; Jovan, 2002). These specifics make process manufacturing *complex* and *uncertain* (Scherer, 1995; Allweyer and Scheer, 1995). The complexity of the production process arises primarily from the required linking of various sub-processes, each of which affects the quality of the final product. The uncertainty of the

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process industry is expressed above all in actual product quality and achieved production rate. It is desirable to achieve high and uniform product quality in every industrial process plant, but the non-uniformity of the quality of basic raw materials, deviations in process parameters, failures of technological equipment, outages in energy supply, and often also combinations of various indeterminate reasons render any prediction of the level of both quality and production rate a risky business. The specifics of process manufacturing usually have a great influence on the scheduling process, and the focus here is to maintain stable production within given constraints (Jovan, 2002).

There is clearly a need for further research in the area of efficient scheduling algorithms for industrial applications. In the following, we present the problem of practical implementation of scheduling principles during the design and implementation of the dedicated algorithm for individual batch launching in one of Slovenian biggest chemical works, the producer of titanium dioxide.

3. Case study

3.1.Description of technological process

The titanium dioxide sulphate (TiO_2) production process consists of a series of batch and continuous sub-processes. One of them is the two-stage gel washing with intermediate bleaching (Fig. 1) (Jovan and Hauptman, 2002). The aim of this sub-process is to remove some impurities from the suspension of titanium dioxide (like iron, vanadium, magnesium, chromium, etc).



Fig. 1. The filters on the first stage of the subprocess two-stage gel washing with intermediate bleaching.

The gel is washed first in one of four pressurised candle filters 1.2 on the primary washing and then in one of three filters 2.2 on the secondary washing, while bleaching occurs between the both washings in discharge vessels 1.3 (Fig. 2) which are on the first

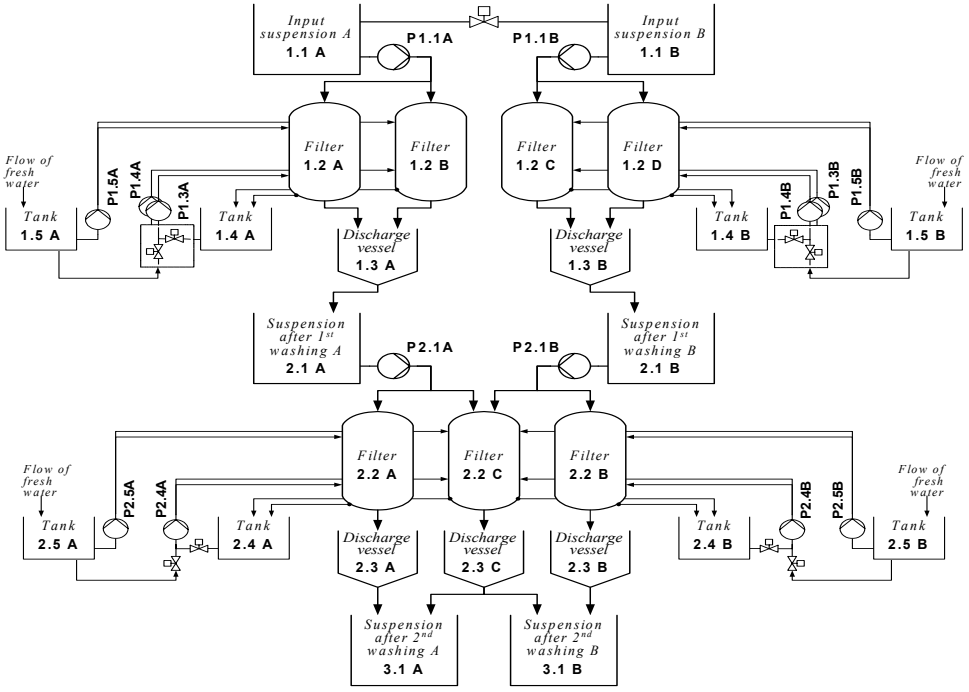


Fig. 2. Scheme of two-stage gel washing sub-process.

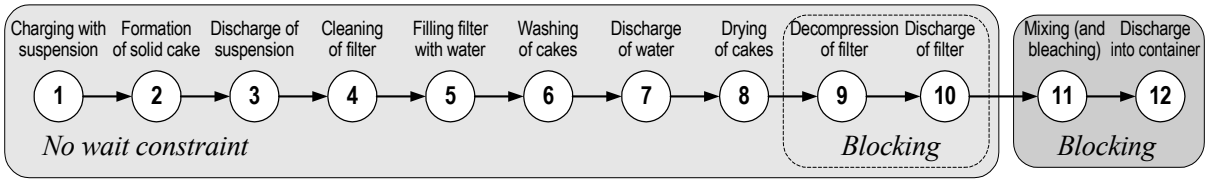


Fig. 3. Sequence of batch steps of the gel washing subprocess.

washing stage shared by two pairs of filters. There are some other shared resources as dosing pumps P1.1 and P2.1, washing pumps P1.3, P1.4 and P2.4, spraying pumps P1.5 and P2.5, and compressed air. The filter 2.2C is an emergency reserve and can supplement or replace filters 2.2A or 2.2B. The capacity of the discharge vessels 1.3 and 2.3 is limited so that merely the content of single filter can be discharged at a time. The process is divided into line A (filters 1.2A, 1.2B, 2.2A) and line B (filters 1.2C, 1.2D, 2.2B).

The procedure of the primary and secondary washing of the gel is essentially of a batch nature and consists of twelve steps/operations: 1 – charging filter with suspension, 2 – formation of solid cake, 3 – discharge of suspension, 4 – cleaning of filter, 5 – filling filter with water, 6 – washing of cakes in reverse direction, 7 – discharge of water, 8 – drying of cakes, 9 – decompression of filter, 10 – discharge into discharge vessel and adding of additions, 11 – mixing (and bleaching just after the first washing) and 12 – discharge into container.

All twelve steps of the individual batch are executed successively in the same technological order (Fig. 3).

The main problems regarding scheduling of individual batches in the gel washing process were as follows:

- Due to technological requirements, steps 1–10 of a batch must be completed without interruptions. This fact is implied by the no-wait constraints between all of these batch steps.
- Because of the layout of the technological process, after being processed in a filter the gel must be displaced into a common discharge vessel. This fact demands that the discharge vessel has to be empty at the end of step 9, otherwise blocking occurs.

The actual processing times for each step 1–10 are not fixed but can vary; the reason for the uncertainty of step durations lies in the fact that the changing quality of input suspension, the usage duration of candle meshes, the temperature, the pressure, etc, can affect these steps, but these parameters are not measurable and their influence on the duration of individual steps is not specified.

3.2 Preliminary batch duration measurements

After the experimental production we were able to acquire more relevant data for the duration of individual batch steps. The actual duration times for an individual batch on a single candle filter vary in practice, as expected, mainly due to the non-uniform granularity of solid particles in the input suspension and the current obturation of candle meshes, and for other indeterminable reasons.

The batch steps that contribute the most to the dispersion of the whole batch duration are mostly “formation of solid cake” and “washing of cakes” (see Figs. 4 and 5).

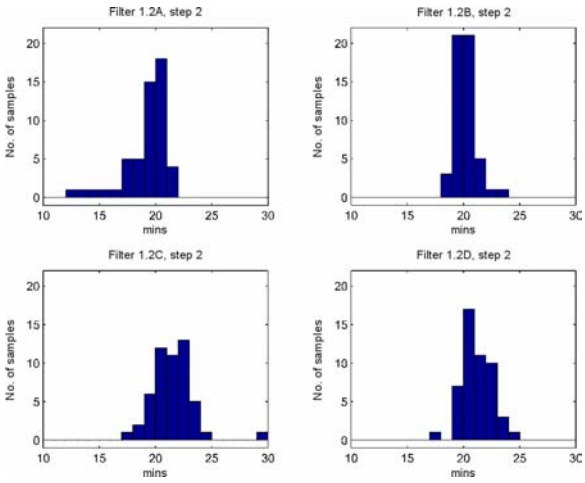


Fig. 4. Dispersion of the batch step “formation of solid cake” duration in the set of 50 samples for Filters 1.2A, -B, -C and -D.

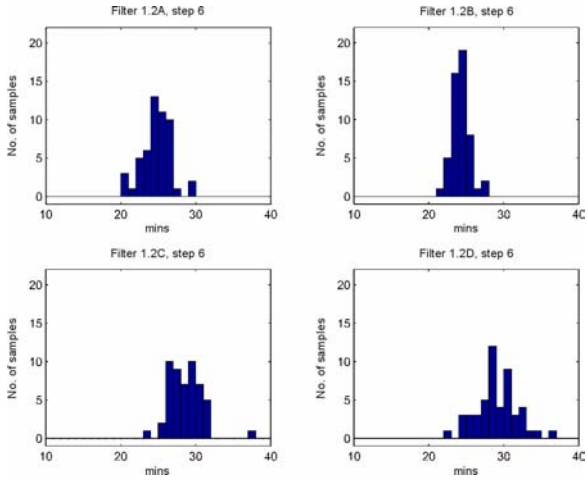


Fig. 5. Dispersion of the batch step "washing of cake" duration in the set of 50 samples for Filters 1.2A, -B, -C and -D.

The average duration of a batch in filter (steps 1–10) can be seen on Table 1.

Table 1
Batch durations on filters of the first washing stage.

Filter	Average batch duration (mins)	Standard deviation (mins)
1.2A	68	+/- 4
1.2B	69	+/- 2
1.2C	73	+/- 4
1.2D	72	+/- 4

The second reason for production rate instability lies in the operator's decision to start an individual new batch. Once started, the batch has to be processed in a filter and then immediately discharged into the common discharge vessel. This means that too-early initiation of a new batch leads to violation of the "no-wait" constraint (waiting results in a degradation of output material), while the too-late start of a new batch results in a reduction of the prescribed capacity.

Both the uncertainty of the subsequent batch durations and manual launching of batches together contribute to the overall production rate instability that can further result in product quality degradation or can lead to the reduction of capacity of the complete TiO_2 production line.

The experimental production phase of the new two-stage gel washing subprocess also showed that the only constraint which really reduce the production capacity are the shared discharge vessels 1.3A and 1.3B in first-stage washing, while other shared resources (dosing, washing and spraying pumps, compressed air) don't affect considerably on the subprocess capacity (Jovan and Hauptman, 2003a). The original problem of sequencing seven independent filters can therefore be simplified into a duplicated problem of initiating just two filters with a shared discharge vessel in each line of the primary washing. The aim was now to obtain a simple and reliable on-line scheduling algorithm to start the batches automatically such that the discharge vessel is equally occupied. Equal occupancy means that the interval between two successive assignments of the discharge vessel is always equal. Equal occupancy of the discharge vessel allows the greatest likelihood of an individual batch being executed without an eventual wait for a free discharge vessel. In this way, the likehood for respecting no-wait and blocking constraints is the greatest and the demand for uniform production rate is respected.

3.4. Dedicated batch-launching algorithm

The proposed algorithm for calculating the most appropriate starting time for a single new batch periodically monitors the current state of the process under observation. It becomes active at the moment both two filters are empty and ready for filling, or when one of the filters is busy and the other one has been discharged and is now idle. When such a case occurs, a current status (F_r or F_W) is assigned to each filter (F_A or F_B), which can be either "running" or "waiting" (that is, $F_A \rightarrow F_r, F_B \rightarrow F_W$ or $F_B \rightarrow F_r, F_A \rightarrow F_W$).

After passing through its *initialisation part*, the algorithm in the *prediction part* calculates the first approximation for the start of a new batch on an idle filter (time to start, t_{wtts}). The calculation takes into account the real duration of all steps that have already been completed and the average duration times for all steps that have not yet been processed. The average duration for all steps, that have not yet been processed on the F_r, are calculated as a moving average value from the last N actual duration times of a particular step. If calculated $t_{wtts} \leq 0$, the new batch on F_w begins immediately.

In the case that F_w is not eligible to start a new batch immediately (time to start, $t_{wtts} > 0$), the algorithm (in its *correction part*) periodically monitors the state of the F_r, and if a new batch step on this filter has been completed, then its average duration time is replaced with its actual duration and a new calculation for the start of a new batch on the idle filter is performed.

Note that this calculation is becoming more and more based on actual duration times (and so more realistic since it reflects the actual state of the observed process). The algorithm alternates between its prediction and correction parts until the condition for the start of a new batch $t_{wtts} \leq 0$ is fulfilled. The basic steps of the algorithm are given below.

Initialisation part

determine $\overline{T}_r, \overline{T}_w$, where $\overline{T}_a = \sum_{i=1}^{n} (\bar{t}_a)_i$

determine $\overline{T}_{rDV}, \overline{T}_{wDV}$

determine t_r, k

determine $T_r^{'} = \sum_{i=1}^{k} (t_r)_i + \sum_{i=k+1}^{n} (\bar{t}_r)_i$

determine $T_0 = 24 * 60 / C_0$ (in mins)

Correction part

- if new batch step on F_r has been completed,
  then $k:=k+1$,
  update t_r,
  recalculate T_r'
- calculate $T = \max \left\{ \begin{matrix} T_0 \\ T_r^{'} \\ \overline{T}_w \\ \overline{T}_{rDV} + \overline{T}_{wDV} \end{matrix} \right\}$

Prediction part

determine $t_{wtts} = \frac{T}{2} + \left(T_r^{'} - \overline{T}_w \right) + \frac{\overline{T}_{rDV} - \overline{T}_{wDV}}{2} - t_r$,

where:

F_r	the filter where the batch is running
F_w	the idle filter, waiting for a new batch launch
C_0	the desired number of batches/day
T_0	expected time interval for a single batch launch on an individual filter
T	estimation of real time interval for a single batch launch on an individual filter
$\overline{T}_r$	average batch duration time on the active filter F_r
$\overline{T}_w$	average batch duration time on the idle filter F_w
$\overline{T}_{rDV}$	average processing duration time in the discharge vessel in the event that suspension comes from filter F_r
$\overline{T}_{wDV}$	average processing duration time in the discharge vessel in the event that suspension comes from filter F_w
t_r	actual batch duration on F_r from the start to the moment of observation
k	number of a batch steps on F_r completed until the time t_r
T_r'	batch duration time on the active filter F_r, where the average duration times of all completed steps are replaced with the real duration times of these steps
t_{wtts}	prediction of the remaining waiting time for a new batch launching on F_w
n	number of a batch steps on a filter
N	number of samples for calculating a moving average
$(t_r)_i$	actual duration of a completed batch step i on the filter F_r
$(\bar{t}_r)_i$	average duration of a batch step i on the F_r, calculated from the last five duration times of this step, $\bar{t} = \frac{1}{N} \sum_{j=1}^{N} t_j$.

3.5. Validation of the sequencing algorithm

The algorithm was implemented as a stand-alone program module of the existing process control system that is based on Siemens programmable logic controllers and uses the PCS7 programming environment. The prediction of the remaining waiting time for a new batch launching is also shown in the existing SCADA system (Fig 7).

The aim of the first test was to validate the functioning of the algorithm itself (Jovan and Hauptman, 2003b). The algorithm was installed on Line A of the gel washing sub-process in order to get a comparison among batch starting times performed by the algorithm and manual starting of the new batches performed by an operator on Line B.

The current production was moderate so the reference capacity of the algorithm was set to 12 batches/day on each filter. Fig. 6 shows the results of the test.

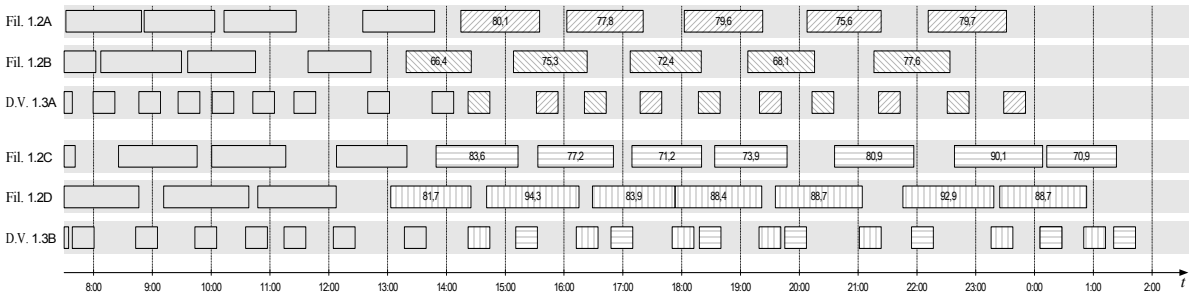


Fig. 6. Results of algorithm testing – experiment No. 1.

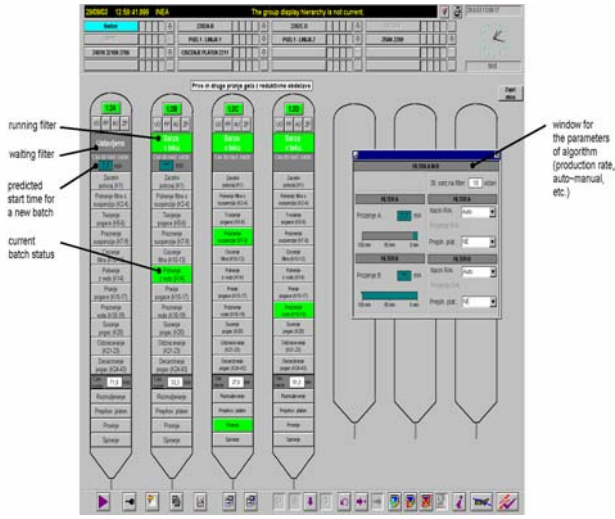


Fig. 7. HMI interface for the on-line batch launching algorithm

From Fig. 6 we notice that the occupancy of the shared discharge vessel (during the period from 14:00 till 22:00) is much more uniform on Line A, where automatic batch launching was performed, compared to Line B where the batches were launched manually. The histograms on Fig. 8 show that the uniformity of batch launching is much higher in the case of automatic launching on Line A (the dispersion of the period of single batch start times is smaller).

The second test run of the algorithm was devoted to an investigation of its behavior in the case where the production capacity of the gel washing sub-process was close to maximum. The automatic batch-launching algorithm was running on Line A and manual starts of the new batches were performed by an operator on Line B. As seen from Fig. 10 the Filter 1.2A on Line A dictates the period of a single batch launching since it's batch durations are longer than those of Filter 1.2B. The algorithm tends to start a new batch on Filter 1.2A as soon the initial conditions for batch launching on Filter 1.2A are fulfilled and simultaneously adjusts the moment of starting a new batch on Filter 1.2B in such a way that the occupancy of the common discharge vessel tends to be uniform.

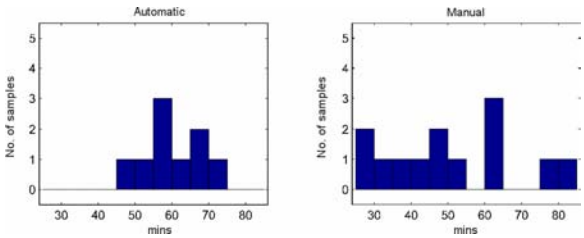


Fig. 8 Histograms of the dispersion of batch launching times for Line A (automatic) and Line B (manual).

The histograms in Fig. 9 show that the dispersion of batch launching times is smaller in the case of automatic launching on Line A, in spite of the fact that the production rate on Line A was higher than on Line B. Two peaks appearing in the histograms on Fig. 9 are the results of the changes in the reference production rate (from 18 batches/filter/day to 15 batches/filter/day) during the experiment.

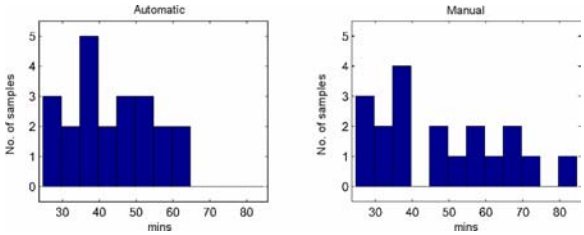


Fig. 9. Histograms of the dispersion of batch launching times for Line A (automatic) and Line B (manual).

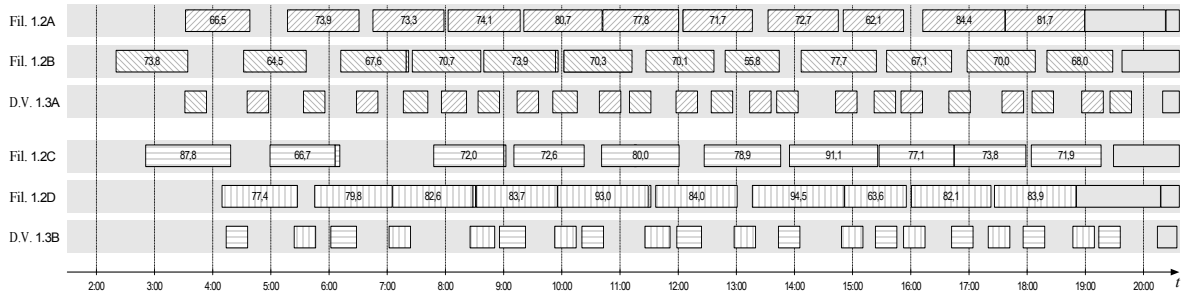


Fig. 10. Results of algorithm testing – experiment No. 2.

4. Conclusions

Within the framework of production scheduling, process manufacturing has many of specifics as compared to discrete flow manufacturing. Production scheduling in discrete manufacturing is focused mainly on the effective utilisation of resources and the tracking of assembly parts while the main objective of scheduling in process manufacturing is stable production with the respect to all process technological constraints. In this article a simple on-line rule-based algorithm has been presented on the real sub-process of TiO_2 production that is capable of predicting the most appropriate launching time for a single new batch, so that no-wait constraints imposed by the technological process are taken into account, blocking of any of batch operations due to shared resources must not occur and the material flow through the subprocess is more uniform.

The proposed algorithm continually adjusts predictions based on the current state, and correspondingly activates a new batch at the earliest possible starting time, simultaneously respecting all predefined constraints and the need for uniform and stable production. The Gaussian of 100 subsequent batches shows (Fig. 11) that the production rate is higher (for 4 to 5%, due to decreased time interval between the starts of subsequent batches) and the dispersion of starting times is lower when the proposed algorithm is applied.

The algorithm was designed dedicately for the subprocess of two-stage gel washing in TiO_2 production plant. However, with minor modifications it is also applicable in other process environments as a system consisting of two reactors sharing a common resource, e.g. a reservoir, is quite common in process industries.

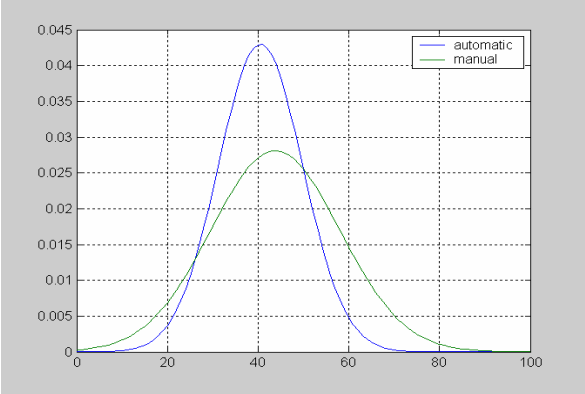


Fig. 11. Gaussian in case of high production rate

The validation of the achieved results shows that the algorithm can significantly contribute to more stable production and can efficiently deal with the no-wait constraints and the non-uniform batch durations of the real case study process.

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