KPIs as the interface between scheduling and control

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Abstract: The integration of scheduling and control has been discussed in the past. While constructing an integrated plant model that may still seem out of reach, scheduling and control systems are increasingly more intertwined. We argue that they are in fact already integrated and give the example of two key performance indicators (KPIs) that are defined in the recent international standard ISO 22400. The focus of this study is on KPIs that consider both planned times and actual times. An amino acid production plant is used in the study, and the production is described from both the scheduling and the control perspective. To illustrate the integration, a schedule is computed containing the planned production times. Resulting measurements from the control system are analyzed for their actual production times using a proposed procedure that detects the start and end time of batches. Using KPIs as the interface between scheduling and control can be used as a strategy for maximizing the plant performance. The study focuses on the process industry.

Keywords: Integration between scheduling and control, key performance indicator, distributed control system, planning and scheduling, batch process.

1. INTRODUCTION

Process industries are industries in which raw materials are physically or chemically transformed, or where energy and material streams interact and transform each other. Examples of such industries are: chemical and plastics, pulp and paper, iron and steel, mining, and food processing industries (IVA-M353, 2006). The industries are typically both raw material and capital intensive. The process industry is dominated by raw material and energy costs, which makes it essential to minimize these costs by efficient use of resources; equipment, assets, material, energy, etc (Lindholm, et al., 2013).

The production in the process industries is often highly automated by the use of various IT/software systems. The production is planned and scheduled by a Production Planning and Scheduling System (P&S). P&S generates a strategy of how to utilize the resources in the plant in order to produce a set of products, often with the goal of minimizing the total production time (make span) or production costs. P&S therefore provides “planned times”, i.e. the planned and scheduled time that is required to perform the activities in the production. A Distributed Control System (DCS) carries out the execution of the production. The DCS normally contains a number of functionalities including regulatory control, management and optimization of stability, safety and quality, as well as means for capturing the “actual times”, i.e. the actual time used to perform the production activities.

It is important that the P&S, DCS and other systems, that on one hand make decisions on their own also can work in a collaborative manner. This is described in e.g. the international enterprise-control system integration standard ISA95-Part1 (ISA, 2010).

In the past, efforts to integrate scheduling and control systematically have not been successfully implemented in real life (Shobrys and White, 2002). The main reason for this is that the focus has been either to mathematically combine two different philosophies into a single model, or to broaden the scope towards an area with a different time scope and physical complexity (Engell and Harjunkoski, 2012).

In this paper, we claim that in practice, scheduling and control are already integrated, as information is exchanged between the systems, either manually of automatically, and the paper includes examples. The efficiency of the resources in the production plant can be evaluated through key performance indicators (KPIs). The KPIs can be defined according to the international standard (ISO 22400, 20014), and generated by means of modern analytics solutions. This information can have an impact, for instance, on the processing time or the selection on which product to produce next. The action derived from the information can be either triggered manually by an operator or automatically through the collaboration between P&S and the DCS based on specific rules or coordination algorithms.

This paper describes a use-case consisting of a batch process in which amino acid is produced. The paper does neither discuss the fundamentals of DCS systems (mathematical modelling of the plant, PID control etc) nor the fundamentals of scheduling (e.g. optimization algorithms etc). Instead it discusses how the P&S and DCS can seamlessly interact and how it opens possibilities to find synergies and optimize various aspects within the area of enterprise-wide optimization (Grossmann, 2009).

The use-case gives examples of how the P&S and the DCS systems are integrated, and the information exchange between the two systems is discussed both from the
scheduling and control perspectives. Building on this use-case the paper also presents two example KPIs which use information from both the P&S and the DCS. The KPIs are defined in the ISO22400 standard (ISO, 2014). In the first example, the KPI ‘Effectiveness’ relates the planned production time with the actual production time per product and equipment and thus forms the basis of comparison between different products and equipment. In the second example, the energy consumption of the planned production is related to the actually consumed energy for the production in the KPI ‘Energy effectiveness’. The KPIs have target values defined, and are computed using information from the P&S and data from the DCS systems. The consequences of a KPI deviating from its target value can be a) to improve the production and therefore impact on the actual production performance or b) to adjust the planned values according to the historical data.

The paper starts by providing background information about scheduling and DCS systems as well as about KPIs and their calculations (Chapter 2). Thereafter follows a description of the case study i.e. the amino acid production plant (Chapter 3), as well as some discussion (Chapter 4). The paper ends with conclusion (Chapter 5).

2. BACKGROUND

Production plants are automated on the control level, and for batch processes often include a scheduling solution. Fig. 1 summarises the interaction between control and scheduling and most importantly the data exchange. In short, scheduling provides information concerning which production orders are carried out at what time and on what equipment. The control system on the other hand passes information back to the scheduling system about the production progress. Information related to energy and assets as well as average actual production durations are used as inputs for the generation of the next schedule.

In this section we briefly discuss the use of scheduling solution and distributed control system (DCS). Some background information is also given on key performance indicators for production processes.

2.1 Scheduling system

The purpose of a scheduling solution is to provide the operators in the plant with the sequence of events, that is, which product is allocated to which processing equipment at what time. In this sense, a scheduling solution is a decision support tool that finds good or possibly optimal planned start and end times for production batches based on given

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| Input                          | Data source                              |
|-------------------------------|------------------------------------------|
| Production cost               | Scheduling / recipe mgmt.                |
| Processing times              | Scheduling / recipe mgmt.                |
| Change-over times             | Scheduling / recipe mgmt.                |
| Production rules              | Scheduling / recipe mgmt.                |
| Capacities                    | Scheduling / recipe mgmt.                |
| Production targets / orders   | ERP / Order management                   |
| Stock inventories             | ERP / Inventory management               |
| Progress data                 | DCS                                      |
| Energy price                  | DCS / Energy management                  |
| Energy constraints            |                                          |
| Equipment availability        | DCS / Asset management                   |
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production targets whilst obeying certain production rules.

Outputs of the scheduling system are:

- Planned Start times, end times and duration;
- Planned Energy and material consumption;
- Planned Orders complete.

The inputs and outputs of the scheduling solution are implemented according to the ISA-95 standard described in Harjunkoski and Bauer (Harjunkoski et al., 2014). The implementation of the ISA-95 standard is the business to manufacturing mark-up language (B2MML), which provides extended mark-up language (XML) schemas. The data transfer is facilitated by .xml files, which can be edited with any off the shelf text editors or read and interpreted by dedicated software. In this way, all data is made accessible through the B2MML interface.

2.2 Distributed Control System (DCS)

A distributed control system (DCS) has the task of controlling a manufacturing process and are at the centre of automating production. DCS connect field devices most importantly sensors and actuators. Besides control, the DCS is used for monitoring as well as asset and energy management. In batch processes in particular, batch management defines sequences of events such as preparing a fermenter, transferring material to fermenter, fermentation, transferring to conditioning and releasing fermenter. The DCS is considered as ‘mission critical’ and has therefore to fulfill stringent safety and security requirements.

Inputs to the DCS from the scheduling solution are the planned start- and end-times of a batch process. The DCS then captures through its sensors the actual process measurements such as power, flow, temperature etc.

2.3 KPI for production management

Key performance indicators (KPIs) quantify the success of a business process or activity. Guidelines for the definition of KPIs exist for organizational functions such as sales and marketing, IT operations and logistics. KPIs should be simple, non-financial and reviewed regularly (Parmenter, 2010). They are typically prepared for a management team and should have a significant impact on the business directives.
Performance measures found to be particularly meaningful for the realization of operational performance improvement have recently been published in the ISO22400 standard. The purpose of these KPIs is to measure the performance of plant operations, and provide decision-making support to the enterprise level. The KPIs are calculated using aggregated measurements from the control layer. The KPI in the standard were initially aimed at discrete manufacturing plants but can also be applied to continuous and batch processes.

Many of the KPI elements used in the KPI description of the ISO22400-2 standard directly relate to the outputs of the scheduling algorithm. In particular, all planned times as listed in Tab. 2 should be a result from the generated schedule. An amendment to the standard, currently under development, introduces KPIs for energy management. Here in particular, the planned energy consumption per production order (PEC) should result from the scheduling solution which in turn requires the knowledge of the planned order quantity (POQ).

Most of the KPIs relate to the past production only and consider the actual production times and quantities. KPIs that combine the information resulting from the scheduling system and the information contained in the DCS are also of interest. In particular, the effectiveness of an asset or work unit (i.e. the comparison of the planned production time versus the actual production time), and the energy effectiveness (i.e. the comparison of the planned energy consumption versus the actual energy consumption).

### Effectiveness

An often used KPI is the effectiveness of an asset or work unit. According to the standard, effectiveness represents the relationship between the planned target cycle and the actual cycle. It is expressed, equation (1), as the product of the planned runtime per item (PRI) multiplied by the produced quantity (PQ) divided by the actual production time (APT).

\[
\text{Effectiveness} = \frac{\text{PRI} \times \text{PQ}}{\text{APT}}
\]

The actual production time (APT) is the actual time during which a work unit is producing. It includes only the value adding functions. The planned runtime per item (PRI) is a parameter that is maintained in the scheduling system.

The APT can be estimated directly through measurements on the relevant assets. One of the most straightforward ways of computing it is to use the current signal corresponding to the actual production time. A simple method to define the actual production times from the current time trend \(x_i\) associated to the different batches \(n\in N\) is in the following procedure.

**Step 1.** Convert the current signal to a binary signal in order to determine whether the motor is switched on (above a defined threshold) or off (below the threshold). The current will never drop to zero due to measurement errors and artefacts.

\[
y_i = \begin{cases} 
1 & x_i \geq \theta \\
0 & x_i < \theta 
\end{cases}
\]

**Step 2.** Eliminate short periods where the motor is switched off since these periods do not indicate a change between two batches.

\[
y_i = \begin{cases} 
1 & \delta_i = 1 \\
0 & \delta_i = 0 
\end{cases}
\]

where \(\delta_i\) is defined as

\[
\delta_i = \begin{cases} 
0 & i : k_{\text{off,end}} - k_{\text{off,start}} > K_S \\
1 & i : k_{\text{off,end}} - k_{\text{off,start}} \leq K_S 
\end{cases}
\]

Here, \(k_{\text{off,start}}\) is the start of the off period and \(k_{\text{off,end}}\) is the end of the off period within the sample \(i\). \(K_S\) is the length below which an off period is considered insignificant.

**Step 3.** Eliminate short periods where the motor is switched on since these do not indicate a change between two batches.

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Table 2. KPI elements of the ISO22400 standard that are possible outputs of the scheduling system.

| KPI                | Name                        | Description                                                                 |
|--------------------|-----------------------------|----------------------------------------------------------------------------|
| POET               | Planned order execution time| The planned order execution time shall be the planned time for executing an order. |
| POT                | Planned operation time      | The planned operation time shall be the planned time in which a work unit can be used. The operation time is a scheduled time. |
| PUST               | Planned unit setup time     | The planned unit setup time shall be the planned time for the setup of a work unit for an order. |
| PBT                | Planned busy time           | The planned busy time shall be the planned operation time minus the planned downtime. |
| PRI                | Planned runtime per item    | The planned run time per item shall be the planned time for producing one quantity unit. |
| PEC                | Planned energy consumption per production order | This value has a planning aspect and can be used to create an ideal planning scenario. It is
determined from the calculated energy consumption multiplied per planned order quantity (POQ). |
| POQ                | Planned order quantity      | The planned order quantity shall be the planned quantity of products for a production order (lot size, production order quantity). |
Figure 2. Process schematic of an amino acid production plant.

\[ y_i = \varepsilon_i \]
\[ y_i = 1 \]
\[ y_i = 0 \]

(5)

where \( \varepsilon_i \) is defined as

\[ \varepsilon_i = 1 \]
\[ i : k_{on,end} - k_{on,start} > K_e \]
\[ \varepsilon_i = 0 \]
\[ i : k_{on,end} - k_{on,start} \leq K_e \]

(6)

Here, \( k_{on,start} \) is the start of the on period and \( k_{on,end} \) is the end of the on period within the sample \( i \) lies. \( K_e \) is the length below which an off period is considered insignificant.

Energy effectiveness

Energy consumption awareness is increasingly becoming more important in industrial production processes. Monitoring and assessing the energy consumption by equipment or production order allows comparison and evaluation amongst these equipment or production orders. In order to assess different entities the energy effectiveness is defined for each equipment or work unit and product by comparing actual and planned energy consumption.

\[ \text{Energy effectiveness} = \frac{\text{PEC}}{\text{AEC}} \]

(7)

The planned energy consumption is listed in Tab. 1 and calculated as

\[ \text{PEC} = \frac{p \cdot \text{POET}}{\text{POQ}} \]

(8)

where \( p \) is the planned average power, POET the planned order execution time and POQ the planned order quantity as defined in Tab. 2. The actual energy consumption (AEC) is the measured energy consumption per produced quantity (PQ). PQ is the quantity that a work unit has produced in relation to a production order.

The AEC is computed as follows

\[ \text{AEC} = \frac{\int_{t_0}^{t_f} p(t) dt}{\text{PQ}} \]

(9)

where \( p \) is the power and APT the actual production time of the produced quantity. The energy effectiveness is calculated for each production order by considering POQ and PQ for the PEC and AEC respectively.

3 CASE STUDY – AMINO ACID PRODUCTION

Amino acids are used in animal feed and as flavour enhancers. Its production can be described in three steps. The first two production steps of amino acid are pre-fermentation and fermentation from sugar, which acts as the substrates for enzymes, see Fig. 2. This part of the production is usually a
batch processes with parallel equipment that can be chosen alternatively for each production order. The fermented sugar is then, in the third production step, transformed into specific amino acids such as Threonine, Lysine or Glycine. This is a continuous production process with different stages, including inactivation, ultrafiltration, crystallization and drying. The continuous production process is very energy intensive requiring significant amounts of steam and electricity. In the case example, the amino acid plant consists of three pre-fermenting stages, three fermenters and three production lines, as illustrated in Fig. 2. It is important to note that the case example is based on a real production process but significant changes have been made for confidentiality reasons. All production data shown in this section are taken from a real process to illustrate the concept of integrating control and scheduling through KPIs. The results of the scheduling solution and the KPI calculation are described.

### 3.1 Scheduling solution

The scheduling solution, illustrated in Fig. 3, is configured to reflect the amino acid plant, Fig.2. Production rules are implemented such that the three products (Threonine, THR, Lysine LYS and Glycine GLY) can be allocated to any pre-fermenter or fermenter but only to their dedicated production line. A weekly, optimized production schedule is shown in Fig. 3 where different production orders are indicated by different colors. The schedule shows the start and end times of each batch on each equipment as well as the planned duration. In addition, stock levels and the total energy consumption for the complete process are displayed in the bottom section of Fig. 3.

### 3.2 Effectiveness per batch

To compute the effectiveness per batch, the procedure of computing the actual processing time (APT) from a process measurement as described in Sec. 2.3 is applied to the trend data shown in Fig. 4. Start- and end-times as well as the APT for Batches 1 to 4 are indicated in the figure and overall effectiveness is computed and summarized in Tab. 3. The resulting table allows the comparison of batches.

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**Fig. 4. Electrical current signal of batch process for batches scheduled in the amino acid process (pre-fermentation).**

**Fig. 5. Power consumption over time for fermentation stage and three batches. The actual power is compared to the planned power from the scheduling system.**
Table 3. Effectiveness of pre-fermentation batches.

| Quantity | Unit | Bth 1 | Bth 2 | Bth 3 | Bth 4 | ACT  Hours |
|----------|------|-------|-------|-------|-------|-----------|
| ACT      | Hours| 23.5  | 22.1  | 5.1   | 14.2  | 353 (2006) |
| PRI      | Hours| 22    | 22    | 5     | 14    |           |
| Effectiveness | % | 94%   | 100%  | 98%   | 98%   |           |

Table 4. Energy effectiveness of pre-fermentation batches.

| Quantity | Unit | Bth 1 | Bth 2 | Bth 3 | Bth3 |
|----------|------|-------|-------|-------|------|
| POET     | Hours| 12    | 12    | 20    |      |
| APT      | Hours| 14:13 | 13:55 | 15:48 |      |
| POQ      | T    | 40    | 40    | 60    |      |
| PQ       | T    | 41.6  | 42.2  | 51.3  |      |
| Planned power | W  | 200   | 200   | 200   |      |
| PEC      | kWh/t| 60    | 60    | 66.7  |      |
| AEC      | kWh/t| 71.9  | 64.3  | 63.4  |      |
| Energy effectiveness | % | 83%   | 93.3% | 105%  |      |

3.3 Energy effectiveness

The power consumption for three batches in the fermentation stage is shown in Fig. 5 together with the planned power consumption as assumed in the scheduling solution. Note that the overall energy consumption of the plant is indicated in the schedule shown in Fig. 3. Plotting the area under the curve in Fig. 5 indicates that the integral as defined in Eq. (9) is computed. The resulting KPI of energy effectiveness for each of the three batches is given in Tab. 4. The energy effectiveness can exceed 100% if the actual energy consumption is lower than the planned energy consumption.

4 DISCUSSION

KPIs are usually evaluated against a target and a comparison is made. The effectiveness KPIs described in this paper take both planned and actual values into account as shown in Fig. 6. These KPIs may deviate from their targets. If this is the case there are two possible actions that feed back to either the scheduling or the control system.

One option is that the process is improved resulting in a better control result and a shortened actual production time. This action can be maintenance or changing of process equipment. Alternatively, the production rules as noted in the scheduling system may be corrected. If the actual order execution time is always longer than 22 hours and the planned order execution time is 20 hours it will probably be wise to adjust the planned order time in the production rules of the scheduling system.

![Fig. 6. Integration of scheduling and control via KPI feedback.](image)

There are several questions arising from this integration that is initially only loosely coupled. An important aspect is the choice of the interval – should there be feedback every day, week or month? Is it possible to feed back the information more often? Another question concerns automatic detection of deviation from the KPIs’ targets. The KPI standard ISO22400 can act as a catalyst to bridge the gap between control and scheduling communities as well as researchers and engineers applying control and scheduling to their processes. It can serve the purpose of encouraging a dialogue between these communities.

5 CONCLUSIONS

In this paper, we describe the practical integration between scheduling and control by combining output information from both systems and putting them into context. The resulting KPIs can then be fed back to each system to further action. This coupling can be loose or tight, depending on the implementation and the business processes in the company. Further discussion between scheduling and control experts relating to KPIs within the standardization community are required to drive the integration further and bring the two approaches closer together.

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