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Hierarchical Scheduling and Utility Disturbance Management in the Process Industry

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Abstract: The integration of scheduling and control in the process industry is a topic that has been frequently discussed during the recent years, but many challenges remain in order to achieve integrated solutions that can be implemented for large-scale industrial sites. In this paper we consider production control under disturbances in the supply of utilities at integrated sites together with the integration towards production scheduling. Utilities, such as steam and cooling water, are often shared between the production areas of a site, which enables formulation of an optimization problem for determining the optimal supply of utilities to each area at the occurrence of a disturbance. Optimization in two timescales is suggested to handle the scheduling and disturbance management problems in a hierarchical fashion. The suggested structure has been discussed with companies within the chemical process industry. A simple example is provided to show how the structure may be used.

Keywords: Production control, hierarchical control, disturbance rejection, chemical industry, process control, optimization problems

1. INTRODUCTION

The chemical industry has during the past decades become a global marketplace with strong competition between manufacturers (Tousain (2002)), and this requires a more agile plant operation to increase flexibility and decrease production costs (Backx et al. (1998)). Planning, scheduling, and control are some key features that have large economic impact on process industry operations (Shobrys and White (2002)). Planning and scheduling in the process industry are two areas that are not easily distinguishable, and the border lines for these areas are diffuse (Kallrath (2002)). Most authors, e.g. Kallrath (2002), Huang (2010), Engell and Harjunkski (2012), and Rawlings and Amrit (2009), define planning as the activity to make production, distribution, and inventory plans, and scheduling to decide the timing of actions to execute the plan and make use of the available resources. A more general definition of planning is given by APICS (2013) as "the process of setting goals for the organization and choosing various ways to use the organization's resources to achieve the goals". The stated timescales for the two activities varies, but usually, planning is said to work on a time period of one or more months, and scheduling on a horizon of weeks. Some work has been done on integrating planning and scheduling, either by combining them and solving the

planning and scheduling problems simultaneously or by various decomposition techniques. An extensive review is provided in Grossmann and Furman (2009). The topic of integration of planning and scheduling with control, on the other hand, is a topic that still has not received much attention in the literature (Grossmann (2012); Craig et al. (2011)). This topic is also viewed differently by different authors, mainly because of different interpretations of the area of control, which can be said to work in timescales of both milliseconds, minutes and hours. Shobrys and White (2002) and Engell and Harjunkski (2012) provide a good view of the activities that have to be integrated and describe the current practice and challenges for integrating the planning, scheduling and control functions in the process industry. A lot of case-specific contributions regarding integration of scheduling and control have also been made, of which Harjunkski et al. (2009) provide an excellent overview. In Tousain (2002), an hierarchical approach for integrating scheduling with control is presented, but here only a single plant/area is studied, and the focus is on multi-grade plants. In the current study, a hierarchical approach to integrate scheduling with production control (on a timescale of hours) is suggested. The approach focuses on disturbances in the supply of utilities at one site with several connected production areas with continuous production. Utilities, such as steam and cooling

water, are often shared between the production areas at a site and management of these disturbances thus becomes an interesting topic, especially at integrated sites where production areas are connected by the flow of products. The work presented in this paper is produced in collaboration with process industrial companies, in particular with Perstorp, that is a world leader within several sectors of the specialty chemicals market (Perstorp (2013)).

2. HIERARCHY MODELS

To clarify at which levels of the physical and functional hierarchy of an enterprise the current study is focused, the role-based equipment hierarchy, functional hierarchy and scheduling hierarchy are defined in this section.

2.1 Role-based Equipment Hierarchy

According to the standard ISA-95.00.01 (2009), there are five levels of the role-based equipment hierarchy of an enterprise; the enterprise, site, area, production unit, and unit level. Traditionally, the area of process control is focused on control of production units, e.g. reactors or distillation columns, or of the connection of production units. This would correspond to the production unit level or area level of the equipment hierarchy. In this study, the focus is on the area and site levels of the hierarchy; on control of the production in the different areas of a site. The areas at a process industrial site are often connected, such that one area produces raw materials for other areas. This is in Wassick (2009) denoted an *integrated site*, and in process flow scheduling (PFS) a *process train*. Changing the production rate in one area, e.g. due to a disturbance, may thus affect the production in several other areas at the site. An example of an integrated site with six production areas and three buffer tanks is given in Fig. 1.

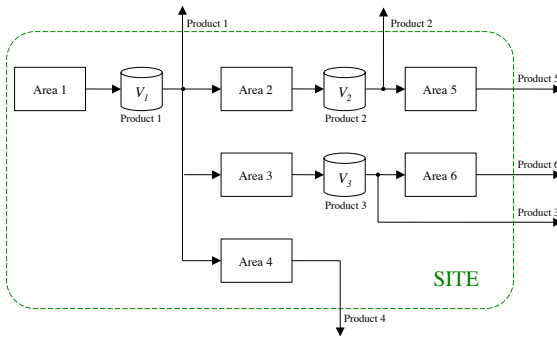


Fig. 1. Example of an integrated site.

2.2 Functional Hierarchy and Scheduling Hierarchy

The functions that are used for operating an enterprise are often viewed in a hierarchical structure. In papers that discuss the integration of different functions, such as production planning, scheduling and control, 'integration pyramids' like the one in Fig. 2 (left) are commonly used. These pyramids might look quite different, which is no surprise since the people working in the field of process control come from many different areas (Tousain (2002)). In this paper, we stick to the definition in the standard ISA-95.00.01 (2009), as presented in Fig. 2 (right).

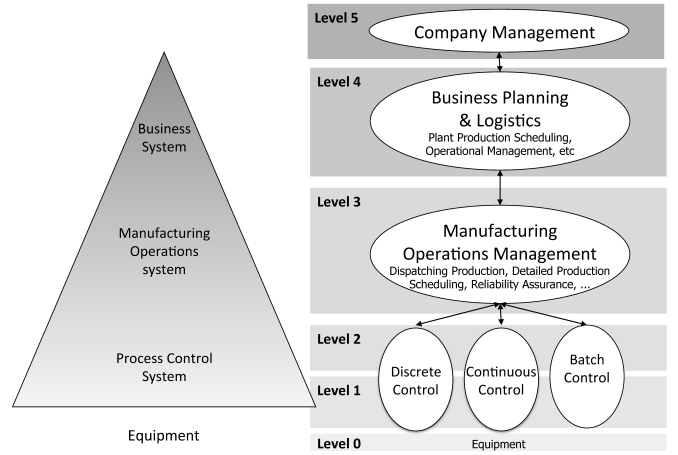


Fig. 2. Functional hierarchy of an enterprise.

The levels represent activities at various timescales, where level 1-2 include activities with the shortest timescales such as sensing and reading (milliseconds, seconds, minutes), level 3 includes activities with a longer timescale such as scheduling (minutes, hours, weeks) and level 4 includes activities with an even longer timescale such as planning (days, weeks, months).

There is also a scheduling hierarchy presented in the appendix of standard ISA-95.00.03 (2005), see Fig. 3. This hierarchy is derived from common terms used in APICS dictionary (Blackstone and Cox (2004)) and ISA-95.00.03 (2005)). The figure could be extended with a control layer at the very bottom, visualizing the fact that control and scheduling are tightly coupled.

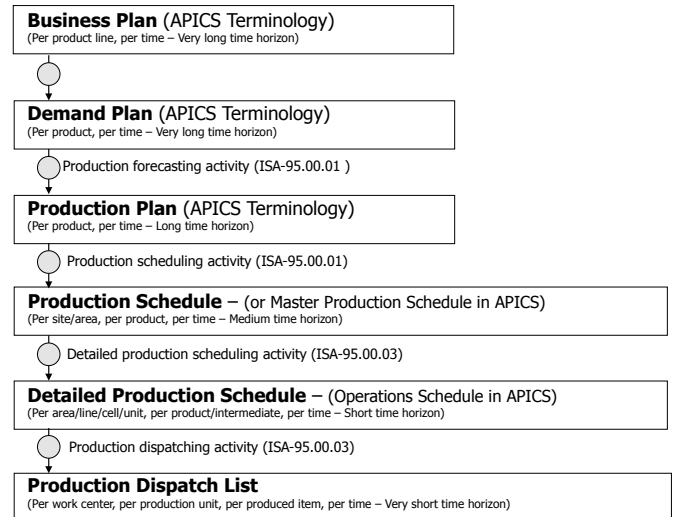


Fig. 3. Scheduling hierarchy of an enterprise.

In this paper, we have adopted a hierarchical scheduling approach in which the short-term scheduling (referred to as 'detailed production scheduling') takes care of the fifth level in the scheduling hierarchy, whereas the long-term scheduling (referred to as 'production scheduling') takes care of the fourth level.

3. UTILITY DISTURBANCE MANAGEMENT

Utilities, such as steam and cooling water, are often shared between several production areas at a site. Disturbances in the supply of utilities might therefore affect production at large parts of the site. Examples of utility disturbances are too high temperature of the cooling water, too low or too high pressure in the steam net, or an electricity failure. Utilities may be interpreted as volumes, or power, which all areas have to share (Lindholm and Giselsson (2013)), which means that if one area uses less of a utility, there is more of the utility available for other areas. This enables formulation of an optimization problem that aims at dividing the utility resources among the areas at a site at a utility disturbance. A reasonable goal is to try to divide the resources such that the total loss of revenue is minimized. Formulation of such an optimization problem is discussed in Lindholm and Giselsson (2013). The optimization problem becomes particularly interesting for integrated sites, where both the plantwide nature of utilities and the area interconnections contribute to the complexity of the problem. In this paper, the optimization problem is part of the detailed production scheduling activity, as described in section 4.

4. STRUCTURE FOR SCHEDULING AND UTILITY DISTURBANCE MANAGEMENT

We suggest the structure for integrated scheduling and disturbance management that is visualized in Fig. 4. In the production scheduling layer, a production schedule is set that serves as a reference for the detailed production scheduling. The suggestion is that the production scheduling activity produces a production schedule one month ahead and updates the plan every day. This time step and horizon has been suggested after discussions with Perstorp. The detailed production scheduling layer determines how

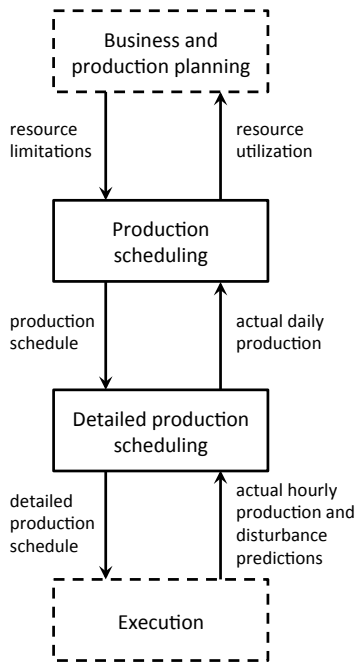


Fig. 4. Suggested structure for scheduling and utility disturbance management.

the production should be controlled to handle utility disturbances in an economically optimal way. The suggestion is that this activity operates on horizon of one day and updates the schedule every hour. The resulting accumulated daily production is reported to the production scheduling layer every day. The detailed production scheduling also has an interface to the actual site, where the schedule is executed. This could be done e.g. by the operators at the site or using model-predictive control (MPC). Measurements from the site report to the detailed production scheduling layer how the production was actually conducted. This layer also gets a prediction of the disturbance trajectories over the horizon for the detailed production scheduling.

Our suggestion is to run both the production scheduling and detailed production scheduling in receding horizon, and produce a new schedule in every time step, but an alternative would be to only redo the schedule only when needed, as in Kadam and Marquardt (2007). The suggestion to perform the production scheduling and detailed production scheduling separately is to make the solutions transparent and understandable for the process operators. If the solutions are not accepted by the operators, they will not be used in the long term (Engell and Harjunkski (2012)). Also, the current apprehension among most authors in the field, among others Engell and Harjunkski (2012), Kadam and Marquardt (2007) and Tousain (2002), seems to be that a hierarchical approach is currently the only realistic one to tackle industrial-size problems, since the fully integrated solution often leads to large, complex and nonconvex optimization problems. In the following subsections, the production scheduling and detailed production scheduling activities, as suggested in this paper, are described in more detail.

4.1 Production Scheduling

The upper level in the hierarchy, the business and production planning, gives information on a long term perspective (strategic) to the lower level, production scheduling. The information (input) needed for making the production schedule can for example be different kinds of capacity, levels of storage for different products, incoming orders, planned maintenance and transports. The production scheduling also uses the actual production per day as an input together with the input from the upper level to make a production schedule for a month ahead divided into daily time periods. The objective of the production scheduling is to make a production schedule that serves as an input to the lower level in the hierarchy, the detailed production scheduling. The production schedule can be seen as a plan on the tactical level. The production schedule is executed every day to update the monthly plan. The outcome of the production schedule is decisions like how much to produce of each product at each area on a specific site. The purpose when making the production schedule is to minimize the difference between the planned production and the actual production with respect to related costs for overproduction and underproduction respectively, and the levels of the contribution margins for each product are also taken into account. The forthcoming decisions on the level below the production scheduling, the detailed production scheduling level, can in turn be seen as decisions on an operational level.

4.2 Detailed Production Scheduling

The objective of the detailed production scheduling is to handle daily utility disturbances at the site in order to minimize the economical influence of these disturbances. Reference values for the sales of products are given by the production schedule, and predicted utility disturbance trajectories are also given as input for the detailed production scheduling. If the volume interpretation of utilities suggested in Lindholm and Giselsson (2013) is used, this is equivalent to trajectories that describe how much of the utilities that are available at each time instant. This could be represented in percent of how much that is available at normal operation of the site and its utilities. The output from the activity is trajectories that suggest how much to produce and sell at each hour during the day, and how the buffer tanks at the site should be utilized. The detailed production scheduling layer also provides information to the production scheduling layer about how much that was actually produced in total of each product during the day (one time step in the production schedule). This information is used in the production scheduling layer to update the production schedule that gives the reference values for the detailed production scheduling. The detailed production scheduling is performed in receding horizon fashion, such that the operators may update their prediction of the duration, severity and shape of the disturbance every hour. The model of the site that is used for the detailed production scheduling has to contain information about the area and buffer tank interconnections, the maximum and minimum limitations on production rates and buffer tank levels, and at which areas at the site each utility is used. To make the model realistic, start-up costs for areas should also be considered, since start-ups are often very expensive at process industrial sites.

5. AN EXAMPLE

To demonstrate the suggested hierarchy for scheduling and disturbance management, a very simple example is given in this section. This simple setup is chosen to clearly show the integration of the two scheduling levels. More industrially relevant examples are handled in ongoing research. Here, a site with two areas that share one common utility is considered, as shown in Fig. 5. The areas produce one product each, product 1 and product 2, with contribution margin m_i , maximum hourly production q_i^{\max} and minimum hourly production q_i^{\min} for product $i = 1, 2$. The two areas are not connected by the flow of products, which means that the only way they interact is that they share the same utility. Table 1 summarizes the production data for the two products in the example. The production schedule for the two products is denoted q_1^{PS} and q_2^{PS} , and has a horizon N_{PS} of one month (30 days) with time steps of one day. The detailed production schedule for the two products is denoted q_1^{DPS} and q_2^{DPS} , and has a horizon N_{DPS} of one day (24 hours) with time steps

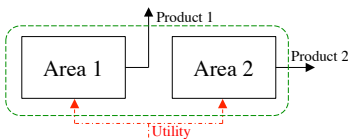


Fig. 5. Two areas that share the same utility.

Table 1. Production data.

	q^{\min}	q^{\max}	m
Product 1	0.1	1	0.5
Product 2	0.1	1	1

one hour. The actual production of the two products that was performed at the production scheduling and detailed production scheduling level are denoted \tilde{q}_i^{PS} and \tilde{q}_i^{DPS} respectively, for $i = 1, 2$. The hierarchy of the scheduling is shown in Fig. 6.

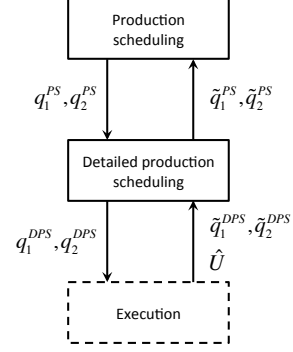


Fig. 6. Scheduling hierarchy in the example.

5.1 Production Scheduling

The production scheduling determines the production schedule, which is updated each day after getting information from the detailed production scheduling on the actual production during the last day. It is also possible that demands $d_i(\tau)$ change from one day to the next due to new incoming orders. The objective of the production scheduling is to minimize the cost for backlog, and the input is daily demands of each product $d_i(\tau)$. Due to possible mismatch in the actual daily production, the initial backlog is set to $B_i(0) = d_i(0) - \tilde{q}_i^{PS}(0)$. Notice that if the actual production during the previous day was greater than the demand, the initial backlog could be negative. As long as there are some demand each day, this does not pose any real problem. Variables for this problem are $q_i(\tau)$, the amount to produce of each product i during time step τ , and $B_i(\tau)$, the accumulated backlogged amount of product i at time step τ . The optimization problem may be posed as the linear program (LP)

$$\begin{aligned}
 & \text{minimize} && \sum_{\tau=1}^{N_{PS}} [B_1(\tau) + B_2(\tau)] \\
 & \text{s.t.} && B_i(\tau) = B_i(\tau - 1) + d_i(\tau) - q_i(\tau) \quad \forall i, \tau \\
 & && N_{DPS} \cdot q_i^{\min} \leq q_i(\tau) \leq N_{DPS} \cdot q_i^{\max} \quad \forall i, \tau \\
 & && B_i(\tau) \geq 0 \quad \forall i, \tau
 \end{aligned}$$

Since the two production areas are coupled only by utility usage, the optimal production scheduling strategy is to adjust the production in the next time step in order to account for the production error, i.e. backlog, according to the plan for the previous time step. If the backlog can not be adjusted at once due to minimum or maximum limitations on the possible accumulated production in a time step, it is instead adjusted in the succeeding step. The production schedule is updated in every time step over the horizon $N_{PS} = 30$ days.

5.2 Detailed Production Scheduling

At a disturbance in the utility, the production in the two areas is limited by the amount of the utility that is available at time t , $U(t)$, according to

$$u_1(t) + u_2(t) \leq U(t) \quad (1)$$

where $u_i(t)$ is the assignment of the utility to area i at time t . It is assumed that the utility is of continuous type, which means that greater assignment of the utility to an area makes it possible to increase production in that area (Lindholm and Giselsson (2013)). It is also assumed that the relationship between assignment of the utility to an area and production in that area is linear, and that zero assignment of the utility gives zero production, i.e.

$$q_i(t) = c_i u_i(t) \quad (2)$$

where $q_i(t)$ is the production in area i at time t and c_i is a constant that is specific for the utility and area i . If $U = 1$ (100 %) corresponds to normal operation of the utility, and the utility is shared equally between the production areas at maximum production, we get $c_i = 2q_i^{\max}$ for $i = 1, 2$, where q_i^{\max} corresponds to the maximum production rate of area i . This means that the constraint the utility poses on the production in the two areas may be expressed as

$$\frac{1}{2q_1^{\max}} q_1(t) + \frac{1}{2q_2^{\max}} q_2(t) \leq U(t) \quad (3)$$

There are also production rate constraints given by capacity limitations:

$$q_i^{\min} \leq q_i(t) \leq q_i^{\max}, \quad i = 1, 2 \quad (4)$$

The detailed production scheduling aims to maximize the total contribution, or minimize the loss, at a utility disturbance. Since the areas are not connected and there are no buffer tanks at the site, the optimization only concerns choosing the optimal production rates for the two areas, given a predicted utility disturbance trajectory, \hat{U} . The production scheduling gives the reference for the accumulated daily production (q_1^{PS} and q_2^{PS}). This production is divided evenly over the each hour of the day to produce reference production rates for the two products at each time step in the detailed production schedule, q_1^{ref} and q_2^{ref} . The optimization problem for the detailed production scheduling may be formulated as the quadratic program (QP)

$$\begin{aligned} & \text{minimize} \quad \sum_{t=1}^{N_{DPS}} [\Delta q_1^2(t) + \Delta q_2^2(t) - m_1 q_1(t) - m_2 q_2(t)] \\ & \text{subject to} \quad (3) - (4) \end{aligned}$$

with $U(t) = \hat{U}(t)$ and $\Delta q_i(t) = q_i(t) - q_i^{\text{ref}}$ for $i = 1, 2$. The horizon for the detailed production scheduling in the example is $N_{DPS} = 24$ hours. The profit maximizing terms $-m_1 q_1(t)$ and $-m_2 q_2(t)$ are gray because they are only included in the cost function when the site is affected by disturbances. For disturbance-free periods, pure reference tracking is performed to avoid overproduction.

5.3 Results

The initial production schedule for the example is shown in Fig. 7. This schedule is updated every day based on the actual daily production the previous day. In the example, utility disturbances only occur at day 2 and 17. All other

days of the month, the detailed production schedule could be executed without deviations from the reference given by the production schedule. Fig. 8 and 9 show the detailed production schedule at days without and with the influence of a utility disturbance. For simplicity, perfect prediction of the disturbance is assumed, i.e. $\hat{U} = U$. In the figures, the current time step in the receding horizon of the detailed production scheduling is hour 12, and both the actual and predicted trajectories are shown. Fig. 10 shows the actual production after the entire month together with the initial production schedule. In the figure it can be seen that at the days where utility disturbances were present, the production was not performed according to the initial schedule. This was corrected by updating the plan and producing more or less of the two products one or more days later. After the entire month, the accumulated production of both products was the same as the planned amount. Both the LP and QP problems were solved using CPLEX.

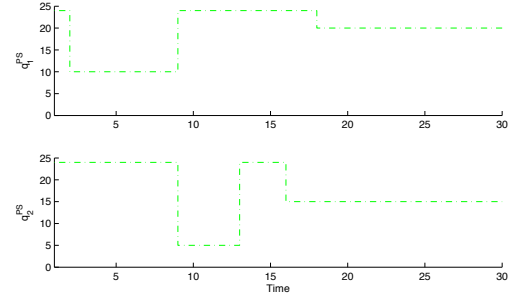


Fig. 7. Initial production schedule.

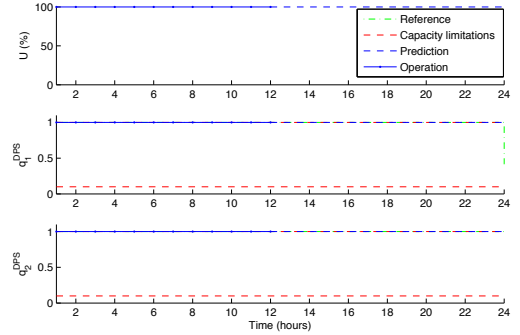


Fig. 8. Detailed production schedule at day 1, hour 12.

This example shows how the structure where a scheduler and a detailed production scheduler operate in receding horizon may be used. A very simple example was presented to keep focus on the structure and avoid optimization problems where the solutions are too complex to understand intuitively.

6. CONCLUSIONS AND FUTURE WORK

A hierarchical approach to scheduling and utility disturbance management for integrated process industrial sites was presented, where the production scheduling and detailed production scheduling are both performed in receding horizon at different timescales. The production

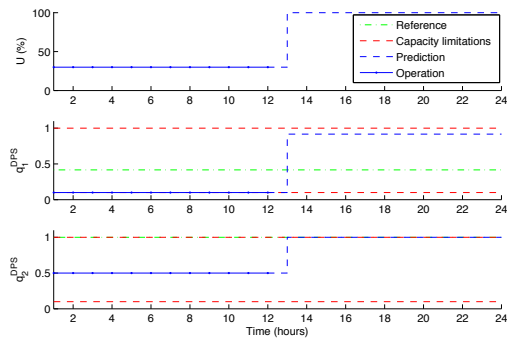


Fig. 9. Detailed production schedule at day 2, hour 12.

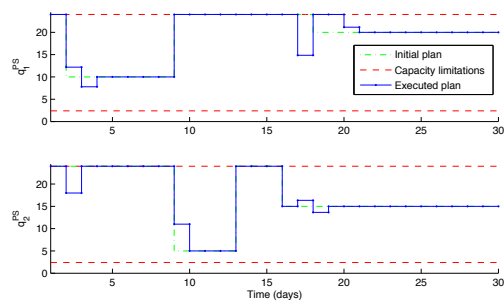


Fig. 10. Initial production schedule and actual production.

scheduling produces a production schedule for a month with time steps of one day, based on e.g. incoming orders, transports, and the results from the detailed production scheduling. The detailed production scheduling handles utility disturbances given estimated disturbance trajectories, and operates on a horizon of one day with time steps of one hour. The reference for sales of products are provided to the detailed production scheduling layer by the production scheduling layer each day of the month. Current research is focused on developing a generic production scheduler that may be used in the hierarchical structure described in this paper. In the example given in the paper, a very primitive production scheduler is used. This could be replaced by a more advanced version, that takes more aspects of the planning into account. The objective is also to improve the model used for the detailed production scheduling, and shape the objective function of the posed optimization problem to really reflect the economic aspects of the production control. The aim is also to try the structure on a real industrial case, and compare the results with current planning methods.

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