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Hierarchical scheduling and 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 obtain integrated solutions that may be implemented at large-scale industrial sites. This paper introduces a general framework for production scheduling (PS) and detailed production scheduling (DPS) using a two-level hierarchical approach. The PS activity generates a monthly production schedule based on information on orders and forecasts, and the DPS activity handles disturbances in production on an hourly basis. The focus is on disturbances in the supply of utilities, which often cause great losses at process industrial sites. The research has been conducted in close collaboration with Perstorp, a world-leading company within several sectors of the specialty chemicals market. A specification list provided by Perstorp has been used as a starting point for formulating the PS and DPS activities as optimization problems. An example that is inspired by a real industrial site is presented to show how the PS and DPS may operate and how the integration of these two functions behaves.

1. Introduction

The chemical industry has during the past decades become a global marketplace with strong competition between manufacturers (Tousain, 2002), which motivates the need for optimizing the operational efficiency. Planning, scheduling, and control are key features that have large economic impact on process industry operations (Shobrys and White, 2002). These areas are often not easily distinguishable, and border lines between the areas are often diffuse (Kallrath, 2002). Common definitions are that planning is 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 (Kallrath, 2002; Rawlings and Amrit, 2009; Huang, 2010; Engell and Harjunkoski, 2012). The timescales in which the activities operate also vary. Usually, planning is said to work on a time scale of one or more months, and scheduling on a horizon of weeks. For control in the process industry, it is much harder to find a general definition both of the timescale and the activities to be performed, because of the many different interpretations of process control. In this paper, two activities are handled, which are denoted *production scheduling* (PS) and *detailed production scheduling* (DPS), in line with the definition in ISA-95.00.03 (2009). The PS operates on a horizon of one month, and the DPS on a horizon of one day. The activity of production scheduling is sometimes denoted *scheduling*, and detailed production scheduling is denoted *advanced control* in other papers, e.g. in Shobrys and White (2002) and Engell and Harjunkoski (2012).

The vague definitions of the activities to be performed at the planning, scheduling, and control level also makes it more difficult to define what is meant by the integration of these areas. Some work has been done on integrating planning and scheduling, either by combining them and solving the planning and scheduling problem simultaneously, or by various decomposition techniques. An extensive review is provided in Grossmann and Furman (2009). The topic of integrating planning and scheduling with control, on the other hand, is a topic that still has not received much attention in the literature (Craig et al., 2011; Grossmann, 2012). Shobrys and White (2002) and Engell and Harjunkoski (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 Harjunkoski et al. (2009) provide an excellent

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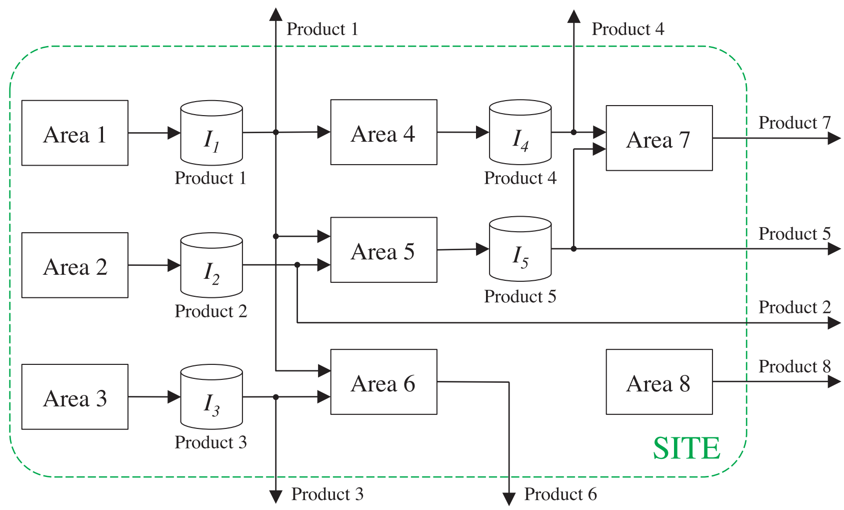

Fig. 1. Example of an integrated site.

overview. In Tousain (2002), a hierarchical approach for integrating scheduling with control is presented, but only a single plant/area is studied, and the focus is on multi-grade plants. In the current study, a hierarchical approach for integrating the PS and DPS activities is suggested. The focus is on one process industrial site with several connected production areas.

The focus in this paper is on production scheduling for chemical process industries with continuous production. Several models for scheduling for chemical sites have been proposed previously, but the majority of these, e.g. the models suggested in Kondili et al. (1993), Neumann et al. (2002), and Maravelias and Grossmann (2003), handle the scheduling of batch processes. The state-task network (STN) introduced in Kondili et al. (1993) is also used by, among others, Ierapetritou and Floudas (1998) and Shaik et al. (2009) to formulate production scheduling models for continuous production sites. However, these studies focus on the unit level of the equipment hierarchy rather than the area/site level that is relevant for the current study. General frameworks for chemical production scheduling are suggested by Sundaramoorthy and Maravelias (2011) and Maravelias (2012), but these frameworks focus on batch processes and are not as intuitive for sites with continuous production.

Perstorp is a world-leading company within several sectors of the specialty chemical market. The company has ten production sites around the world, where each production site is divided into about 5–10 production areas. The production sites typically run in a continuous mode, without any product changes or grade changes. The aim of Perstorp is to run its production sites in a well-defined way even when there are site-wide disturbances such as disruptions in a utility or raw material. In order to do so, decision makers at Perstorp have generated a specification list containing demands and desires for the production scheduling. This list is used as a starting point for finding models for the PS and DPS that are generic enough to be applied to all its production sites. The specifications are listed in Section 4, and formulated as optimization problems is Sections 5 and 6.

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 with continuous production; the enterprise, site, area, production unit, and unit levels. Traditionally, the area of process control is focused on control of production units, e.g. reactors or distillation columns, or on control of some connected 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.

If modeling at the site/area level in the hierarchy should be performed, and the area dynamics are fast compared to the dynamics of the production network, the production in an area can be assumed to be directly proportional to the inflows to the area (i.e., the dynamics within the area are ignored). This assumption is also made in Lindholm and Giselsson (2013). The assumption can be expressed as

$$q_{ijt}^{\text{in}} = q_{jt} a_{ij} \tag{1}$$

where q_{ijt}^{in} is the inflow of product i to area j at time t, q_{jt} the production in area j at time t, and a_{ij} is called the conversion factor between product i and product j. In Fig. 5 in Section 5.2, the notation is shown in a flowchart of an example site.

2.2. Functional 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). The levels represent activities at various timescales, where levels 1–2 include activities with