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# Production Scheduling in the Process Industries: Current trends, emerging challenges and opportunities

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## Abstract

This paper discusses the current trends and defies associated with production scheduling, both from an industrial and academic perspective. First, the new challenges that appear in the context of globalized and competitive economies are addressed. They stem from the need of considering scheduling as a building block of the Advanced Planning Systems (APSs) that nowadays participate in Supply Chain Management (SCM) functions. They are primarily associated with business process coordination and information integration requirements. Then, main features, strengths and limitations of current academic proposals are briefly addressed. Finally, some of the reasons for the slow acceptance and modest penetration of these research results are highlighted. Thus, challenges and opportunities to be faced in order to alleviate the miscommunication of the academic and industrial worlds are pointed out.

**Keywords**: Process Scheduling and Operations, Advanced Planning Systems, Supply Chain Management, Business Process Coordination and Integration

## 1. Introduction

Nowadays, most companies experience a growing international competition and recognize the needs of supply chain (SC) efficiency and responsiveness. These requirements originate from the pressures of shortened product life-cycles and increasing customer demands on a great variety of low-price, high quality products. On top of these needs, there are also higher expectations on accurate deliveries, with short lead-times and always rising customer service levels. The growth in globalization, and the additional management challenges it brings, has motivated interest in global Supply Chain Management (SCM). Successful SCM requires a change from managing individual functions to integrating activities into key SC business processes.

In order to compete, companies must be more efficient, transparent, and agile. This requires real-time visibility into their business operations and the ability to react if needed. To achieve this goal, Operational Intelligence (OI) focuses on providing on-line monitoring of business processes and activities as they are executed, in assisting them by identifying and detecting situations which correspond to interruptions, inefficiencies, threats, bottlenecks, etc., and communicating them to relevant stakeholders.

Since many process industries try to adopt SCM and OI philosophies, this introduces new pressures into the way they perform their scheduling activities. The trend is to adopt scheduling systems (SSs) which no longer are employed as isolated support applications. On the contrary, they are perceived as integrated building blocks of these advanced management tools. Thus, new tendencies and problems have appeared. Modern SSs are nowadays part of the Advanced Planning Systems (APSs) that industry is quickly adopting (Stadtler and Kilger, 2005), and new functional and non-functional requirements have arisen for them. These new requisites are discussed in Section 2, along with more traditional industrial demands not covered yet in most SSs.

On the other hand, from the academic side, there has been enormous progress on methodologies to tackle scheduling problems in the last two decades. A brief overview of their strengths and limitations, as well as current trends, is presented in Section 3. Despite the flourish of approaches, a dichotomy between the industrial and academic worlds is still evident. Requirements that SSs need to face in a competitive and globalized context, as well as capabilities and characteristics that academic proposals need to incorporate to be accepted by the industrial community, are discussed in Section 4, which summarizes emerging challenges and opportunities.

## 2. Industrial practice: Activities in the context of Advanced Planning, Commercial Scheduling Systems and OI applications

As organizations strive to focus on core competencies, they have increased the manufacturing outsourcing of some components and intermediate products and have reduced the ownership of raw materials sources and distribution channels. Thus, the number of different partners along extended SCs has progressively grown. This led in most cases to complex planning situations having multiple products, manufactured at multiple work centers in multi-site production systems, which are transported by third or fourth party logistics. Under these circumstances, scheduling is crucial for achieving the timely and cost-effective execution of industrial production processes. However, the pressures being faced now are much higher than those identified by Shah (1998).

In the context of the burdens that globalization and networked economies pose, advanced concepts on supply chain management (SCM) have emerged. According to Stadtler and Kilger (2005), the goals of SCM can be achieved by resting on two pillars: the integration of the organizational network and the coordination of material, information, and financial flows. In turn, the coordination pillar comprises several building blocks: proper use of information and communication technology, process orientation, and advanced planning. All of them are quite relevant to define the context in which a scheduling system must operate and to specify the requirements it must fulfill.

Advanced Planning includes long, mid and short-term planning levels. Software products, referred as Advanced Planning Systems, are now available to support these tasks. APSs aim at complementing existing ERP systems and overcoming some of their weaknesses. ERPs have traditionally addressed planning tasks poorly and have focused on a single company. On the contrary, modern APSs are being designed for inter-organizational SCs. APSs try to find feasible, near optimal plans across the SC as a whole, while potential bottlenecks are considered explicitly (Stadtler and Kilger, 2005). In terms of software components, an APS means a broad group of integrated software applications developed by various software vendors, such as i2 Technologies, Manugistics, Oracle, SAP, AspenTech, etc. Fig. 1 shows the structure of a generic APS. For the sake of brevity all of these systems are not discussed in detail; however, some advanced ones, such as Aspen Plant Scheduler (http://www.aspentech.com) or SAP Advanced Planner and Optimizer (SAP-APO) (http:// http://help.sap.com) are worth to be mentioned, since they exhibit a high degree of integration of their scheduling component with the other planning modules comprising the system. Regarding solution methodologies included in the scheduling element, the first of these systems uses decision rules and heuristics, while SAP-APO employs the ILOG´s optimizer library, as other vendors, but pre-defined model formulations are not made completely explicit. SAP APO offers several solution approaches, among them mixed-integer linear programming (MILP), constraint programming (CP) models and evolutionary algorithms.

Embedded optimization models seem to be a problem associated with APSs since explicit, high level representations are not available yet. On the contrary, SAP APO as well as other ASP providers, have coded their models in C or C++. As suggested by Kallrath and Maindl (2006), this fact has several consequences: (i) Before starting an implementation of an APS, a thorough investigation of the applicability of the vendor's models is necessary, and (ii) knowledgeable users in modeling techniques are required to embed pre-defined SAP-APO models, as well as "own" optimization models. The users (consultants, schedulers) not only would need to understand the underlying scheduling approach, but also know how to make it interoperate with the transactional and master data that the APS handles.

Despite advances in the integration of the various planning functions, APSs do not seem to have specific tools to address reactive scheduling problems. To properly tackle them, besides having specific solution approaches, the integration of the APS with the Manufacturing Execution System (MES) is required. As pointed out by Harjunkoski et al. (2008), this integration is mandatory for the correct management of manufacturing operations and to perform control activities. Such integration should rely on the pillars of standard representations (ANSI ISA-95, ISA-88), business process modeling and service oriented architectures.

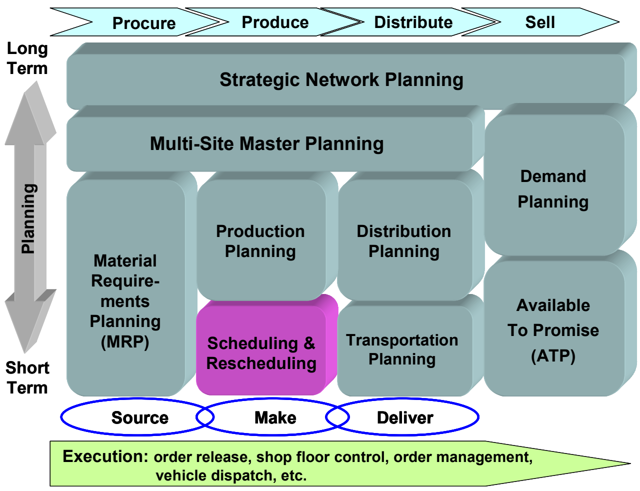


Fig.1. Components of a Generic APS

In addition to APSs, many commercial SSs have matured over the last decade. Over 100 software applications of Finite Capacity Scheduling (FCS) systems are available according to APICS (http://www.apics.org). However, the use of these systems is not widely spread yet. Among them is worth to mention some products that are academic spin-offs. For instance, applications like VirtECS Schedule from Advanced Process Combinatorics (http://www.combination.com) and SchedulePro from Intelligen (http://www.intelligen.com) have powerful graphical capabilities and include interactive scheduling tools (ISTs), features that are always demanded by the industrial world.

However, the integration of these systems, similarly to other commercial packages, with the organization planning modules and the MES, does not seem to be straightforward.
Finally, it should be mentioned that most APSs and commercial SSs do not have explicit support for basic OI functionalities, like process traceability as well as the automatic and seamless generation of metrics and key performance indicators.

## 3. Research Efforts: Strengths and limitations of the academic proposals

Nowadays, the academic community is able to address more difficult and larger scheduling problems than those tackled twenty years ago. The most significant research efforts are highlighted in some excellent reviews, like the ones of Li and Ierapetritou (2008), Méndez et al. (2006), Floudas and Lin (2004), Kallrath (2002), Pekny and Reklaitis (1998), Pinto and Grossmann (1998) and Shah (1998). Usually, problems are solved by resorting to MILP formulations. Optimal solutions are many times reached for small and medium size problems, with reasonable computational efforts. This success basically comes from the remarkable advances in modeling techniques, algorithmic solutions and computing technologies that occurred in the last decade.
One of the key elements of the various MILP approaches involves time representation; current formulations can be classified into discrete-time and continuous-time models. Other essential issues are related to the characteristics of the production environment being considered: sequential or network process, operation modes, storage policies, type of critical resources, changeovers, etc. This wide scope of features has led to a variety of formulations that are generally oriented to properly address particular classes of problems. Despite recent advances, there is no general formulation that can tackle the various classes of problems with the same efficiency. For instance, it is not clear the extent to which methods aimed at addressing complex network processes, can also be successfully applied to other structures commonly found in industry, such as the multistage one. Efficiency is also highly dependent on the adopted objective function; however, no extensive evaluations have been done in this respect. Nowadays, nobody denies that schedule measurement is a critical aspect of the scheduling problem, which is multiobjective, multiattribute in nature. Schedules mean different things to different people and are used by various organizational groups in distinct ways. Even having a single scheduler involved in the evaluation process, the question of how to deal with the tradeoffs between the different metrics of interest is hard to address without keeping the human involved (Kempf et al., 2000). Few advances in this respect have been made by the academic world.
Formulations based on CP have also gained interest recently (Maravelias and Grossmann, 2004; Roe et al., 2005). The PSE community has started to adopt CP, mainly in combination with MILP models, because these techniques are complementary to each other when a cost or profit related objective function is chosen. Nevertheless, this hybrid approach has a poor computational performance when other objective functions related to time are tackled.
An analysis of current proposals shows that they are becoming more mature and progress is made along various research lines. Some works have improved the representations from a computational point of view (Janak and Floudas, 2008). Others have concentrated on the expressive power of the model, to be able to capture more realistic features (Giménez et al., 2009). Moreover, recent proposals have extended previous formulations to move the frontiers of the problems being tackled, thus addressing the integration of scheduling and design (Castro et al., 2005), planning and scheduling (Maravelias and Sung, 2008), of mid and short-term scheduling (Janak et al.,

2008a), etc. In fact, there is a new tendency to generalize basic formulations to address a wider scope of problems. Fortunately, the latest reactive scheduling proposals (Vin and Ierapetritou, 2000; Méndez and Cerdá, 2004; Janak et al., 2008b, etc.) follow this trend and share the basic representation with their predictive scheduling counterparts, facilitating the integration of predictive and reactive scheduling components.

## 4. Emerging challenges and opportunities

As seen, the industrial and academic worlds have given considerable attention to the scheduling problem and enormous advances have been achieved. Due to lack of space certain important problem features, such as uncertainty, or some solution techniques, as metaheuristics and evolutionary approaches, have not been treated in this work.
Despite this progress, most of the theoretical research done during the last 15 years is of limited use in the real world. In fact, while researchers provide answers to toy cases, practitioners have difficulties in explaining their needs and exploiting the opportunities that could come out from the utilization of advanced scheduling approaches. Naturally, this academic-industrial dichotomy has several causes. Some are pointed out below:

- Currently, a SS is one of the blocks of an APS, which in turn is part of a SCM system. This fact imposes requisites of applications' integration and business process coordination. On the other hand, academic proposals have focused on algorithms and computational performance; thus, they lack a business process view and do not have an explicit domain representation, which would facilitate integration. For instance, most MILP approaches rely on very sophisticated formulations (grounded on STN and RTN models, and artificial notions like time points, events and time grids) that do not have a direct mapping to ordinary problem elements, as they are perceived by industrial practitioners and to master data, as handled by industrial information systems. In consequence, to bring in industry representations which are oriented towards efficient problem solving, there is a need to revalorize the design of interfaces (CAPE-OPEN, 2001), as well as the development of ontologies and meta-languages.
- The role of the human scheduler needs to be stressed at the various problem solving stages: Problem definition, solution process and results analysis (Weirs, 1997). Schedulers must be able to manipulate, customize and tailor models/solution approaches as part of their day-to-day work. This manipulation should be done by means of high level constructs and visual languages. Visual modeling is nowadays used for many purposes in several industrial sectors, but not in the scheduling field yet. Besides, schedulers need to achieve independence from IT and domain specialists. Modeling should become almost as natural as sketching and scribbling. Moreover, the use of high level graphical tools for solution analysis must also be a routine practice. Finally, cooperative work among the various stakeholders must also be supported.
- Academic scheduling approaches need to be comprehensively evaluated. The current focus on just computational performance and solution quality needs to expanded to cover other features like ease of implementation and usability, robustness, extensibility, etc. (Pekny and Reklaitis, 1998). The adoption of a scheduling benchmarking service (Cavalieri et al., 2007) and the definition of new industrial-size benchmark problems (Kallrath, 2002) would certainly help in this respect.

By addressing the two first issues, an extra-added value will be obtained. The number of errors attributed to miscommunication between various organizational areas would drop due to the seamless integration of enterprise data into the SS and the proper dissemination of scheduling results. Similarly, the number of errors attributed to the scheduler would decrease substantially with his/her full articulation within the SS.

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