Models and Algorithms for Production Planning and Scheduling in Foundries – Current State and Development Perspectives

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Abstract

Mathematical programming, constraint programming and computational intelligence techniques, presented in the literature in the field of operations research and production management, are generally inadequate for planning real-life production process. These methods are in fact dedicated to solving the standard problems such as shop floor scheduling or lot-sizing, or their simple combinations such as scheduling with batching. Whereas many real-world production planning problems require the simultaneous solution of several problems (in addition to task scheduling and lot-sizing, the problems such as cutting, workforce scheduling, packing and transport issues), including the problems that are difficult to structure. The article presents examples and classification of production planning and scheduling systems in the foundry industry described in the literature, and also outlines the possible development directions of models and algorithms used in such systems.

1. Introduction

Scheduling is an important management activity within a plant. Finding a good feasible schedule by which costs and lead times can be reduced, is often a very complex and difficult task. A short-term planning problem in foundries is especially complicated, because production processes in such manufacturers are of a continuous-discrete type. Complex and comprehensive character of the modeled objects requires development of flexible tools which would be useful for solving the considered problem.

In spite of the large number of theoretical works reported on production planning and scheduling, there are very little industrial applications. The aim of this paper is to present the current state in this field and to provide directions for the development of production planning and scheduling systems that can be applied to real-world production environments. Section 2 deals with the models buildings and solving techniques that are used in planning and scheduling systems. In the field of OR application to planning and scheduling in foundries, the literature is not extensive. We could find only a few papers dealing with this problem that are discussed in Section 3. In Section 4, the development directions of industry-specific integrated planning and scheduling systems are outlined. The conclusions are drawn in Section 5.

2. Planning and scheduling approaches

Production planning in the classical approach involves the separate treatment of planning and scheduling processes. The main objective in production planning is to fulfill customer demand at minimum total cost. At the medium-term level,

production planning consists of Material Requirements Planning (MRP), Master Production Schedule (MPS), and Capacity Resource Planning (CRP). These problems are well explored and described in the literature, and can be viewed as a set of balance equations. Short-term planning (scheduling) is carried out on a daily or weekly basis to determine the assignment and sequencing of tasks (clients' orders) to production units. Due to interconnections between different management levels and interdependence of the decisions made at the various time horizon, planning and scheduling decisions should be made simultaneously. Hence, the corresponding planning methods should be integrated as it is shown in Figure 1.
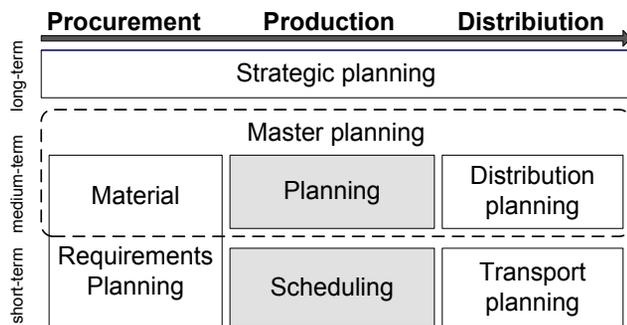

Fig. 1. Decision areas in production planning. Source: [10]

That is why in modern production planning systems the concept of advanced planning and scheduling system (APS) is used. APS is a technology that utilizes optimization algorithms for solving models which simultaneously take into account all the materials and enterprise resources available, while reflecting all the constraints and business goals. This approach considers a large scheduling problem over the planning time horizon and, due to the complexity and size of the problem, developed models are hard to solve without decomposition.

2.1. Scheduling models

The classical models, widely studied in literature, are divided into three classes [15]:
1. single machine, parallel machine and job shop models,
2. production systems with automated material handling,
3. lot scheduling models.

The detailed description of these models can be found in [15].

The classical models are not sufficient to cover real production planning and scheduling problems. Scheduling research carried out during the last decade is very intensive. Many researchers were motivated by the need to create scheduling models that comprise most of the features that arise in practice. However, Potts and Strusevich [16] in their extensive survey of scheduling process mention only a small number of such enhanced models that in fact are the extended version of the models introduced in earlier decades.

The enhanced scheduling models studied during the last few years include [16]:

1. online scheduling in which information about jobs arriving in the future is unknown,
2. scheduling with batching when several jobs can be processed together,
3. supply chain planning and scheduling models that integrate several of the operational functions that form the supply chain,
4. scheduling with machine availability constraints, for example caused by planned maintenance.

To meet integrating challenge, researchers and practitioners have proposed production planning models which include scheduling submodels. These formulations can be grouped into three classes [10]:
1. detailed scheduling models,
2. relaxations/aggregations of scheduling models,
3. surrogate models derived through off-line analysis of the manufacturing facilities.

Scheduling formulations focus on detailed modeling of actually feasible resources and constrains in a manufacturing environment. They typically include unit-task assignments, sequencing of tasks assigned to each unit, and inventory and utility constraints.

The relaxed/aggregated model is obtained by removing some of the constraints, or by aggregating some of the decisions of the original scheduling formulation. A common approach is to reject the sequencing constraints and variables, or combining them in different ways.

In *off-line surrogate models* the resource constraints and production costs of a facility are calculated off-line. Once generated they can be incorporated into the integrated formulation what significantly reduces computational afford to find near-optimal solution.

2.2. Solution techniques

Solution strategies for the integrated planning scheduling problem can be grouped into three classes [10]:
1. hierarchical, if the high-level integrated (master plan) problem is solved first, and then this solution is an input to the lower-level scheduling subproblem to obtain a complete solution,
2. iterative, if there is a closed loop from the scheduling submodels back to the master problem,
3. fullspace, if the integrated formulation contains detailed scheduling submodels for each planning period, so its solution provides all the necessary information.

A wide variety of techniques and tools can be used in the solution approaches mentioned above. There are various typologies of decision-making tools in the management and production logistics. Kobbacy et al. [9] divide them into two major classes: Operational Research (OR) and Artificial Intelligence (AI). OR techniques include mathematical programming, network analysis, regression, queuing theory, simulation, and maintenance models. The main AI techniques are: logic and theorem proving, uncertainty management, case-based reasoning, data mining and symbolic learning, neural networks, heuristic searching methods, and intelligent agents.

Eom and Kim [7] point out the growing role of artificial intelligence in decision support systems in the area of production

management. These observations are also confirmed by Kobbacy et al. [9].

An interesting question is how practitioners perceive the importance of the outlined problems and the use of tools to solve them. Many cross-sectional studies conducted in recent decades, among others in USA [3], Western Europe and New Zealand [2], highlighted the divergence of academic research and real applications in production management practice. According to practitioners a low importance of the academic works results from the following:

− problems to which they refer are not encountered in practice,
− benefits from their use are not clearly defined,
− management is effective without the use of these tools,
− executive staff has no knowledge of these techniques,
− the models have unrealistic assumptions.

It confirms the need for development of simple and easy to use tools for real-life integrated production and scheduling problems.

3. The examples of solving the foundry planning problems

There are only a few studies available in the field of OR and AI application for production planning and scheduling in foundries. Creighton and Nahavandi [5] have proposed discrete event simulation for system design of a melt facility. Although the primary goal of this approach is system design, it can be used to identifying good operating policies that maximize throughput. Thus, production planning is made possible by analysis and simulation of key production and organization factors. The simulation model can be used to evaluate production capacity, schedule production tasks and detect bottlenecks limiting the system performance.

Ugarte at al. [22] have tested hybrid approach combining a genetic algorithm and a real-time discrete event simulation model for rescheduling decision in aluminum foundry that produces batches of alloys in the cast lines. In the ERP-controlled environments the authors have implemented on-line scheduling model where simulation model expresses the plant logic and is responsible for evaluating the GA solutions, and genetic algorithm is employed as optimization engine. The SAP xApp Manufacturing Integration and Intelligence (xMII) provides a connection between ERP databases and scheduling model. The main objective of the optimization is to generate a sequence minimizing the use of high-quality metal for clients' orders requesting low alloy grades.

Santos-Meza at al. [17] have studied a lot-sizing problem in an automated foundry when the production bottleneck is the furnace. The problem consists of two decisions: what alloys should be produced in the furnace in each period, and the quantity of items to be produced in each molding machine. The objective function is to minimize the total production costs. The authors have proposed problem-specific heuristic to solve large practical integer programming problem. In this case some production constraints are relaxed without loss of optimality.

Araujo et al. [1] have dealt with the same problem prevalent in small market-driven foundries. A mixed integer programming

(MIP) formulation of the problem proposed by the authors is impractical to solve real-life instances in reasonable computing time. As a result, a faster relax-and-fix (RF) approach is formulated: at the R step all integer variables are relaxed and the relaxed problem is solved using local search heuristics developed by authors, while at the F step partially fixed problem is solved to optimality with the CPLEX MIP solver.

More recently, Camargo at al. [4] have considered the similar problem. The authors have proposed the heuristic that solves the problem in a hierarchical way. A genetic algorithm is used to explore a larger set of alloy sequences and a knapsack problem algorithm determines the lot size of the items for each furnace loading. It is worth to mention that the proposed genetic algorithm with the knapsack problem (GAKP) is an open-source software. The computational experiments show that the proposed approach is better than the methods described in the literature.

Voorhis at al. [23] have developed a computer system for generating pouring schedules in steel foundries. The system automates the planning process by estimating the impact of pouring sequences on work in progress (WIP) level. The integer programming model is employed that minimizes the complex cost function, which includes the cost of tooling set-up, late deliveries, WIP inventory, and under-utilization of the production units. The program implements heuristics that can find multiple solutions to integer model, each of which corresponds to a feasible schedule. Because of the number of total variables, finding the exact solution is impossible. The heuristic implements branch-and-bound algorithm to find nearly optimal solution, limiting the number of open branches. The algorithm finds a feasible solution in two stages: the first generates many possible alternatives for assignment of alloys to heats, while second generates a schedule for each of the alternative tasks. Tests show that the proposed system is able to handle realistically sized scheduling problem in a reasonable time.

Teixeira at al. [21] have proposed a binary integer model for production scheduling problems in market-driven foundries. This industry includes many small and medium businesses, with minor or no automation of processes, working with a diversified production, with various metal alloys, in a small series of make-to-order products. The objective is to minimize the cost of manufactured products based on balancing and synchronizing the molding, pouring and finishing steps, aimed at eliminating high stock levels, rationing the use of production resources and foundry furnaces. Synchronization among the three production phases directly reduces production cycle time and indirectly improves quality of products.

Park and Yang [14] have introduced a Linear Programming (LP) optimization model for casting scheduling in job-shop type foundries. They have considered a typical foundry where various castings in different sizes and shapes are made out of molten alloy, which is obtained by melting ingots in a limited number of furnaces with different capacities. In each shift, molten metal is ladled from a furnace until it is used up or production plan is accomplished. Production planning, based on foundryman intuition and experience, often results in either excessive remains or shortage of molten metal. The primary variable in scheduling model is the amount of castings produced in each shift; the authors have argued that the objective function to maximize alloy utilization percentage and entire constraints reflecting real casting

conditions can be represented in linear forms. The LP model generates an optimal casting sequence resulting in the maximum use of molten alloy. Moreover, if raw material is provided in ingots with discrete size, the authors have proposed a scheme of adjusting the number of charged ingots to enhance the utilization of furnaces.

Nonas and Olsen [13] have outlined a scheduling problem for an engineer-to-order foundry that manufactures propeller blades for ships. The production of blades is done in boxes of different sizes, on successive days, according to capacity restrictions with respect to which combination of boxes that can be used simultaneously. The main objective is to find a production plan that minimizes the total number of days orders are late, taking into account the constraints related to the scheduling of the present jobs and resources. The constraints on the resources are quantified by a capacity matrix. The authors proposed a mixed integer linear programming (MILP) formulation together with a production-specific heuristic. The use of heuristic is motivated by fact that the MILP model can be solved with a commercial software (e.g. CPLEX) only for small-sized problems. Existing solvers were not able to handle the larger problems of the foundry since the number of integer variables involved in the mathematical formulation became too large. For this reason the authors have introduced a four-stage heuristic procedure that search among different box-combinations and different job sequences for a production plan in order to minimize the tardiness of clients' orders.

4. Development directions of future planning and scheduling systems for real-life industrial problems

Literature review and the research conducted by the authors at several polish steelmakers and foundries allow for the formulation of the main assumption: it is impossible to develop an universal planning and scheduling model covering wide variety of industrial situations. Every plant and every internal or external supply chain has to be provided with its own, tailored model, as there is no possibility to predict all real-life constraints. In our previous work [20] we presented an evolutionary based framework for production scheduling in a foundry. The proposed approach simultaneously considers planning and scheduling processes in order to achieve the optimality. However, there are problems that still need to be solved before such and similar systems can be successfully implemented in practice.

The first issue with the application of the planning and scheduling systems proposed in literature for real-world production environments arise from the models they use. As it has been shown in the previous sections such models usually base on one of the classical optimization problems like lot-sizing or job shop scheduling. These models are usually tailored to particular problem but, by definition, they do not allow for the inclusion of other important aspects that should be taken into account during production planning and scheduling. There are two possible solutions for this issue. The first one is to abandon traditional mathematical programming formulas and to use more universal planning and scheduling modeling languages. Some attempts in

this field have already been done. Ilog Solutions (now part of IBM), the world-wide biggest vendor of optimization systems for enterprises, developed a language called Optimization Programming Language (OPL). OPL combines traditional mathematical programming with constraint programming (including logical and higher-order constraints) and also provides a natural support for definition of scheduling and resource allocation problems [8]. A simple job shop model written in OPL looks like follows:

```
minimize makespan.end
subject to {
forall(j in Jobs)
 task[j,nbTasks] precedes makespan;
forall(j in Jobs & t in 1..nbTasks-1)
 task[j,t] precedes task[j,t+1];
forall(j in Jobs & t in Tasks)
 task[j,t] requires tool[resource[j,t]];
}
```

while similar model written using the classical mathematical formulas can be expressed as:

Minimise
$$C_{max}$$
subject to
$$\forall i \in O: t_i \geq 0$$
$$(\forall j \in J)(N_{j-1}+1 \leq i \leq N_j-1): t_{i+1} \geq t_i + p_i$$
$$\forall j \in J: C_{max} \geq t_{N_j} + p_{N_j}$$
$$\forall i,j \in O, i \neq j, M_i = M_j : \begin{cases} x_{ij} \in \{0,1\} \\ t_j \geq t_i + p_i x_{ij} - T(1-x_{ij}) \\ t_i \geq t_j + p_j (1-x_{ij}) - Tx_{ij} \end{cases}$$

Unfortunately OPL language is used only by the commercial solver included in IBM ILOG CPLEX Optimization Studio.

A good alternative to modeling in the high level languages is to use languages based on XML. Such languages are usually hardly human readable and require additional editors for modeling purposes, but they can be used without any restrictions and are guaranteed to be understood by every partner in a supply chain. Moreover, such languages can be mixed with other XML languages or can be extended to better suit certain applications. For the purpose of planning and scheduling in real-world industrial applications OASIS (an international organization providing XML standards) develops a worldwide PPS (Production Planning and Scheduling) standard, which is based on Japanese Planning and Scheduling Language on XML specification (PSLX). PSLX project, supported by Japanese universities and companies like Fujistsu, Hitachi and Toshiba, is more than just a language for modeling of planning and scheduling problems. It can be used also for architectural description of an APS system based on agents, and also provides protocols and ontology for information exchange between partners in a supply chain. A detailed description of this language can be found in [19].

Insufficiency of planning and scheduling models can be also addressed by applying the concept of business rules. Business

rules describe the operations, definitions and constraints that apply to an organization. Such rules written in the form of IF-THEN expressions or in the form of decisions tables can be conjoined with the traditional planning and scheduling models to deal with non-standard, technology or business dependent constraints, as well as to guide a solver algorithm. An example of such rule for milling operation is [11]:

```
milling-operation
{IS A operation
WORK-CENTER: milling-center
DURATION {INSTANCE time-interval DURATION: 5}
NEXT-OPERATION: drilling-operation
SUB-OPERATION: milling-setup milling-run
ENABLED-BY: enable-milling}
```

The detailed discussion about using business rules for planning and scheduling can be found in [6].

Another major problem with the traditional models arises from the assumption of deterministic character of their parameters. In reality, however, decision makers should often deal with uncertainty. This problem is extremely important for a make-to-stock production, where demand usually cannot be precisely approximated, but it affects also a make-to-order environment, if a manufacturer frequently deals with orders that have special requirements (uncertainty from technology) or operates on international market (uncertainty of currency rates). Many different methods can be applied in order to reflect uncertainty in planning and scheduling models. Mula et al. [12] have classified those methods into conceptual models, analytical models, simulation models and artificial intelligence based models. According to the authors artificial intelligence approach dominates in the fields of aggregate planning and supply chain planning, and includes expert systems (business rules), fuzzy logic, agent based systems, neural networks and evolutionary algorithms. Regardless of the method, planning and scheduling under conditions of uncertainty is usually a very complex and demanding task. The application of artificial intelligence methods for this purpose is regarded as the most promising one.

More complex models no longer based solely on traditional mathematical programming, but also on constrained programming, business rules and other concepts require more sophisticated methods to solve them. It is necessary to divide planning and scheduling problems into subproblems, simultaneously ensuring that all relations are preserved. Two approaches are typically used: hierarchical approach, discussed in the previous section, and, more recently, agent based approach. In agent based systems the solution of planning and scheduling problem is divided into set of agents which cooperates in order to provide final solution. Particular agents are responsible e.g. for demand forecasting, plan generation, detailed daily schedule generation and for controlling that all constraints and business rules are satisfied. Application of heterogeneous agents in such systems enables any planning and scheduling subproblem to have different solution technique [18]. It is also worth to underline that agent based solvers are parallel by their nature and they can be also easily scaled, so such approach usually does require any additional computer power to be bought by the enterprises. They can use their own computer resources or the computational power of remote computers by applying the idea of distributed computing or even cloud computing.

Last issue with the proper use of the planning and scheduling systems in production practice concerns the data that are used on input. They should be complete, current, cleared, validated and often accepted by the relevant managers. The use of Business Intelligence (BI) solutions together with extract, transform and load (ETL) tools can be very helpful in providing necessary data for all production planning levels. BI systems can substantially complete the data extracted from traditional databases maintained by ERP systems.

5. Conclusions

In this paper the current state-of-the art in planning and scheduling research in foundry production systems is analyzed. Despite many research studies reported in literature, most companies of the process industries still do not have powerful and integrated software solutions for their planning systems. This results from the fact that there are very demanding industry-specific requirements. There is still a gap between the planning systems on the enterprise level and the real-time systems on process level. New concepts and systems to achieve full integration have only being developed recently. Important principles and some examples for solution approaches have been presented in this paper.

These approaches look very promising, but since they are mostly new, there is not much experience available about their effectiveness in practice. It is therefore necessary to turn these ideas into industrial practice, to test and further improve them.

It seems that the major challenges still lie in modeling of resource and business constraints in complex production systems and also with providing appropriate method for simultaneously solving of planning and scheduling problem. On the other hand, advances in optimization techniques and computing power allow to conclude, that complex planning and scheduling models can be effectively solved.

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