Computers in Industry 61 (2010) 112–126

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

Digital enterprise solution for integrated production planning and control

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ARTICLE INFO

Article history:
Received 30 March 2009
Received in revised form 18 May 2009
Accepted 6 October 2009

Keywords:
Production planning and control
Discrete-event simulation

ABSTRACT

Digital enterprise technologies combined with sophisticated optimization algorithms can significantly contribute to the efficiency of production. The paper introduces a novel approach for integrated production planning and control, with the description of the mathematical models and solution algorithms. The deterministic optimization algorithms are complemented by a discrete-event simulation system to assess solution robustness in case of disturbances. The methods are illustrated by describing two prototype systems and by some experimental results obtained in an industry-initiated project.

1. Introduction

The concept of *digital enterprise* – the mapping of the key processes of an enterprise to digital structures by means of information and communication technologies – gives a unique opportunity for planning and controlling the operation of enterprises [22]. Digitalized solutions are capable to connect customer order management with production planning, scheduling and control (PPC in short). On the other hand, the importance of optimization in decision making at various levels of an enterprise has greatly increased over the past decades, as companies invest in complex advanced planning and scheduling systems to replace their out-dated material requirement planning software. Digitalized data and sophisticated algorithms together can provide additional competitive advantage which cannot be achieved by applying solely the latest production technology.

The *scope* of our work is set to complex *engineer-to-order* and *make-to-order* production, where products (like turbines, assembly lines, etc.) are traditionally associated with high quality, advanced, cutting-edge technology. These industries usually require skilled and expensive human workforce. Recently, business focus has shifted from selling products to supplying a combination of products and services (like engineering design, installation, on-site customization, maintenance). Such "extended products" are highly customized and their value is sensitive to the time of the delivery. Human resource intensive repair and recycling activities have to be planned together with normal production. Due to complex production processes and long lead times, production of components often starts before the overall design has been completed, or customization is executed in parallel with some production activities.

In our target sector, a *project-oriented* approach is taken in general for planning and controlling operations. Relying on the conventional wisdom that it can never be wrong to get work done early, existing project planners typically try to sequence activities as early as possible, subject to technological constraints and resource availability profiles. Such methods are only capable of finding a particular solution, without the ability to explore and evaluate alternatives. Hence, they cannot be used for optimization. Further on, manual intervention is typically required to deal with overloaded resources and violated deadlines. According to our experience, medium-term production plans are *re-adjusted manually* time and again, and less than 50% of the original plan is executed finally.

Our *first objective* was to develop intuitive and flexible models and fast, reliable solution techniques that scale-up well also to large production planning and control problems. Hence, we tackled both the medium-term production planning and the short-term detailed scheduling problems as *resource-constrained project scheduling* problems (RCPSPs) [7]. The solution methods had to respect all the main temporal, capacity and material availability constraints and find an optimal trade-off between various costs and due date performance criteria.

Our *second objective* was to find novel, *aggregate formulations* of the production planning problem which ensure the *integrity of results* that are generated on two different hierarchical levels, on various horizons, by using distinct models and solution algorithms. Following the usual planning hierarchy, production planning

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0166-3615/$ – see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.compind.2009.10.008

determines what to do on the medium-term so as to achieve high-level business objectives. On the other hand, scheduling is responsible for refining a segment of the production plan into a detailed and *executable schedule*. However, since the two levels use different models, it is open whether production plans can really be unfolded into feasible, executable detailed schedules. An essential practical concern – especially in make-to-order production – is also that the representation of the planning problem should be generated automatically, from data readily available in *de facto* standard databases of production information systems.

Both planning and scheduling problems are burdened by various *uncertainties* like estimated resource needs, uncertain capacity availability, unspecified activities due to evolving problem definition, uncertain orders, hypothetical projects, uncertain processing times, as well as unreliable delivery dates of necessary components and materials. Any method that neglects these issues is prone to generate *fragile* solutions. Disruptions hardly stop at the boundaries of the particular shop-floor of an enterprise; they spread upwards in the decision hierarchy and even to other members of a production network. Due to reasons of complexity, the direct inclusion of any main uncertainty factor into our RCPSP models was out of question. Hence, our *third objective* was to assess the sensitivity of deterministic solutions and improve the robustness of production schedules by using *discrete-event simulation* techniques.

In the sequel, first we present our integrated approach to production planning and scheduling (Section 2). While we capture problems at both levels of the planning hierarchy as RCPSPs, the details of the models and the solutions techniques are fairly different. Section 3 gives an account of how we built simulation models automatically from common master data and applied simulation techniques for assessing the sensitivity of production schedules. This work had a strong industrial motivation: in Section 4 we present two prototype systems developed for two enterprises operating in the engineer-to-order and make-to-order sectors, respectively. Finally, we conclude the paper in Section 5 and give an outlook for related research activities.

2. Integrated production planning and scheduling

In make-to-order manufacturing environments, *production planning* is responsible for allocating scarce resources to customer orders over time on a medium-term time horizon (3–12 months). Usually the resources and operations are aggregated to obtain manageable problems, and to get rid of unnecessary details [27]. The objective of planning can be either

- to maximize customer satisfaction by minimizing the tardiness of customer orders, or
- to minimize the cost of completing all the customer orders on time, when delayed shipment is unacceptable.

In contrast, *detailed scheduling* deals with the allocation of operations to machines (when more machines are available to perform the same operation) and the sequencing of operations on the allocated resources. The resource capacities and capacity extensions, as well as the time window of every operation is determined by production planning and the scheduler has to take them into account as hard constraints. Usually, production planning determines the calendar week in which an operation has to be completed. The time horizon of scheduling is usually a couple of days or a few weeks. In fact, it makes no sense to make a detailed operation schedule far in the future as this would be inevitably changed due to disturbances and unforeseen events. The objective of scheduling can be to minimize the makespan of scheduled operations with the aim of finding a schedule such that all the operations planned to complete in a calendar week would finish on time.

In project-oriented planning and scheduling each production order becomes a project that has to be carried out from the ordering of materials through manufacturing, assembly and delivery to the customer. The projects compete for the various resources. If there are several long projects that take several months to complete, then the planning of capacity allocation and expansion has to be done at the production planning level, while the daily work requires a detailed schedule of the operations. Both of these problems can be modelled and solved as resource-constrained project scheduling problems, where planning provides constraints for scheduling, and conversely, the planning problem is defined by aggregating the resources and the detailed operation plans of the projects. Below we present in detail the planning and the scheduling problem, and the necessary aggregation procedures. We also discuss qualitative results.

2.1. Project-oriented production planning

In project-oriented production planning, each project is a collection of activities that are aggregated from the detailed operation plans of the projects. The aggregation procedure will be discussed in Section 2.2. The time horizon of production planning consists of several weeks, and the plans specify the progress of each activity of each project in every calendar week. In case of long projects, aggregated activities usually take several weeks, and the progress or intensity of the activities varies over time. Such a variation of activity-intensities can be planned, provided the chosen planning method enables the modelling of variable-intensity activities [9]. Below we introduce such a mathematical programming approach and describe some results obtained with it.

There are various results in the literature for project scheduling with variable-intensity activities. Weglarz [32] considers the model with continuous time and provides analytical results for minimizing the makespan with respect to finite-capacity resources. Leachman et al. [21] provide practical heuristics. The discrete time model with the makespan objective has been studied by Tavares [30]. The problem with activity deadlines, and the objective of minimizing the above-capacity usage of resources is studied by Hans [10], who proposes a column-generation based approach. Wullink [33] suggests a fast constructive heuristic.

2.1.1. Modelling with variable-intensity activities and feeding precedence constraints

The basic building block of our approach is the variable-intensity activity. In practice, an activity typically starts with low-intensity preparatory work and its intensity gradually increases to a maximal level. The fraction of an activity done in time period t is called the *intensity of the activity in time period t*. For an illustration, consider the two variable-intensity activities depicted in Fig. 1. (The horizontal axes correspond to time periods and the vertical axes to intensities.) The intensity of an activity is at most one, and the sum of intensities of an activity sums up to one. Usually, there is a physical limit on which fraction of the activity can be completed during a single time period. This bound is the *maximum intensity* of the activity.

Each activity may require one or more resources and the demand is proportional to the intensity of the activity. Namely, if the total resource requirement of some activity is q_k from some resource k, and the intensity of the activity is x_t in time period t, then it requires an amount of $q_k x_t$ from resource k in time period t. Of course, the intensity may vary over time as there can be other, more urgent activities that require the same finite-capacity resources.