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Fenced in? Stochastic and deterministic planning models in a time-fenced, rolling-horizon scheduling system

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ABSTRACT

We analyze a time-fenced planning system where both expediting and canceling are allowed inside the time fence, but only with a penalty. Previous research has allowed only for the case of expediting inside the time fence and has overlooked the opportunity for additional improvement by also allowing for cancelations. Some researchers also have found that for traditional time-fenced models, the choice of the more complex stochastic linear programming approach versus the simpler deterministic approach is not justified. We formulate both the deterministic and stochastic problems as dynamic programs and develop analytic bounds that limit the search space (and reduce the complexity) of the stochastic approach. We run extensive simulations and numerical experiments to understand better the benefit of adding cancelation and to compare the performance of the stochastic model with the more common deterministic model when they are employed as heuristics in a rolling-horizon setting. Across all experiments, we find that allowing expediting (but not canceling) lowered costs by 11.3% using the deterministic approach, but costs were reduced by 27.8% if both expediting and canceling are allowed. We find that the benefit of using the stochastic model versus the deterministic model varies widely across demand distributions and levels of recourse—the ratio of stochastic average costs to deterministic average costs ranged from 43.3% to 78.5%.

1. Introduction

A significant challenge for production scheduling models is the dynamic nature of the schedule—today's schedule becomes obsolete and must be modified into a new schedule tomorrow; this is the rolling-horizon production scheduling problem. The complexity of rolling-horizon models necessitates heuristic modeling approaches that generally ignore the "rolling" aspect of the problem and optimize the multi-period schedule assuming that it will not be rolled forward. In practice, as time advances and the schedule is rolled forward, the planned production for each period must be revised to account for the realization of stochastic demand from the prior period.

To reduce the number of near-term schedule changes as the schedule rolls forward, many firms enforce (through their scheduling systems) a "time fence"—a period within which changes are restricted. The time fence covers a set number of periods, for example four weeks, and is rolled forward along with the schedule. As the schedule is rolled forward, schedule changes outside the time fence are not constrained. In contrast, within the time fence expediting and cancelation activities incur a penalty (if they are permitted at all).

The rolling-horizon scheduling problem traditionally is addressed heuristically through a linear programming (LP) approach (Salomon, 1991), where future demand is assumed to equal its expected value, and the fact that the schedule will be rolled forward is ignored. We refer to this heuristic approach as deterministic linear programming (DetLP): demand is treated as deterministic in the LP solution process—disregarding the fact that actual demand is stochastic, and ignoring the implications of a rolling schedule. At the beginning of each period, the DetLP produces a new production schedule, accounting for the realized demand as well as the previous period's production plan, the current inventory position, and time-fencing constraints.

If there is no time fence, rolling the schedule forward generates a new production plan (in the DetLP process) that updates production in the upcoming period to compensate for the difference between the expected demand that was used to create the incumbent plan and the realization of stochastic demand for the previous period. The consideration of a time fence changes and complicates the analysis. In particular, an inviolable time fence prevents any expediting and cancelation inside the time fence. In cases where changes to the schedule are permitted inside the time fence (at a cost), the expediting and

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cancelation costs incurred can lead to a lower overall cost (compared to the inviolable time fence) since the solution space is expanded with the relaxation of the (inviolable) time-fence constraint.

In contrast to the more common deterministic approach to production scheduling problems described above, a few existing works have examined the value of a stochastic linear programming solution (StoLP), which accounts for demand variability as schedules are developed. The StoLP is an optimal approach (rather than heuristic) if it considers demand to the end of the horizon. In practice, the StoLP does not scale well across long time horizons (since it has to consider all possible demand convolutions across all periods) and so the StoLP is typically formulated as a heuristic that considers the randomness only for a few periods out (rather than for the entire horizon). To evaluate the relative merits of the deterministic and stochastic approaches over a rolling horizon, researchers have employed simulation, and have found that the stochastic approach offers advantages only in limited situations.

Specifically, we build on Brandimarte (2006), which extends the DetLP model to examine the use of StoLP (as a heuristic) to reflect the variability of demand in a rolling production schedule. Brandimarte does not consider time fences per se, but rather considers that when capacity is "tightly constrained," the ability to secure additional "reactive capacity" can be more valuable than producing safety stock and consequently the benefit of using a stochastic model—in which safety stock is used as a hedging mechanism along with extra capacity—is of little value. In this case, Brandimarte notes that while StoLP results in a lower cost than that of a DetLP formulation, the difference between the two often does not justify the added computational complexity of the stochastic formulation. The model that Brandimarte considers is equivalent to a time fence model where expediting (i.e., the use of reactive capacity) is allowed (at a cost). We test a similar comparison between stochastic and deterministic models and find that the stochastic model can be more attractive when there is the opportunity for *both* expediting and cancelation.

Allowing both cancelation and expediting activities enables the StoLP model to benefit from hedging opportunities. In particular, with both activities available it may be advantageous to schedule additional production because there is opportunity to reduce the schedule (via cancelation) if actual demand is low or to increase the schedule (via expediting) if actual demand is high. Allowing only one adjustment strategy (either expediting or cancelation) may be of limited use depending upon the realized demand, while the two strategies employed together ensure recourse across a broader range of possible outcomes. In addition, having the ability to cancel orders can be more beneficial than having the ability to expedite because of the nature of recourse outside the time fence. In particular, even without expediting, production can be increased outside the time fence (essentially with no limits) when there is a large shortfall. In contrast, if there is a large surplus and demand falls off dramatically, production can be decreased outside the time fence, but only to zero. This means that the surplus could last a long time, if not indefinitely.

The option of cancelations inside the time fence reflects reality for many manufacturers and their customers. As the global economy has suffered through downturns, many businesses, governments, and individuals have responded by reigning in both spending and commitments. In many cases, this has included the cancelation of planned production and/or purchases. However, cancelation of committed orders can come with significant consequences; changes to plans inside the time fence can result in supplier-assessed penalties as the manufacturers seek to recoup some of their costs. Some manufacturers even provide a scale of cancellation fees depending on how far into the manufacturing period the order is. ScintiTech, Inc. specifies on its website that if "25% of the manufacture[sic] period has passed, a 20% order cancellation fee will be assessed." This cancellation fee is increased to 30% for orders 50% into the manufacturing period, 70% for orders 75% in and 100% for orders 90% in.[1] While examples such as this are not particularly unusual in times of economic duress, existing operations management literature does not adequately address the effects of order cancelations in either production or purchasing systems in a rolling-horizon setting.

In the next section, we review the relevant literature covering production planning problems. We then formulate a multi-period model and develop analytical results for upper and lower bounds and for special cases of the problem. Next, through a numeric experiment and simulations, we compare the performance of the stochastic model with the more common deterministic model under varying conditions. We are interested in three aspects of this problem. First, is the benefit to adding cancelation along with expediting such that it allows a significantly higher level of performance than is realized with the expediting-only policy? Second, considering the increased computational complexity, is the magnitude of solution improvement between DetLP and StoLP significant? Third, under what conditions does the benefit from the opportunity to cancel or expedite depend upon the solution methodology (DetLP versus StoLP)?

2. Literature review

Our topic is part of the broad Capacitated Lot-Sizing Problem (CLSP) genre. This term is applied to a range of discrete-time scheduling problems (Sox, Jackson, Bowman, & Muckstadt, 1999). The CLSP has been subdivided into a large number of related problems, but all maintain the common characteristic that time is modeled as being divided into discrete segments. Another extensive body of work treats time in a continuous manner, and generally is referred to as Economic Lot-Sizing Problems (ELSP).

Our problem falls within the stochastic programming sub-group of CLSP problems. Specifically, we are modeling a single-item, single-level lot-sizing problem with recourse. In our case, we define recourse to not only include allowing backlogging of unfilled demand, but also to encompass the use of expediting and cancelation of planned orders. Because our analysis includes a comparison of both deterministic and stochastic approaches, we review the programming literature for both.

2.1. Deterministic programming

A number of papers have presented substantial reviews of elements of the deterministic CLSP literature. Drexl and Kimms (1997) summarized work in the field of lot sizing and scheduling and note that "taking into account that planning in practice has to be done on a rolling horizon basis is yet another topic worth attacking." Staggemeier and Clark (2001) reviewed research on the single-stage lot-sizing and scheduling problem. In addition to providing a basic description of the deterministic lot-sizing problem and its extensions, as well as a discussion of many heuristic solution methodologies, Karimi, Ghomi, and Wilson (2003) provided a thorough review of the CLSP and solution methodologies, which use both exact methods and heuristics. Brahimi, Dauzere-Peres, Najid, and Nordli (2006) reviewed the single-item lot-sizing problem, both capacitated and uncapacitated.

Li, Tao, and Wang (2012) developed an approximation technique for the deterministic lot-sizing problem when demand varies from period to period. Their study highlighted the complexity of extending the standard assumption of steady demand as well as the importance of identifying superior solutions to this problem. Baciarello, D'Avino, Onori, and Schiraldi (2013) compared the performance of eight heuristic approaches to the uncapacitated single item lot-sizing problem and found that, in the case of deterministic demand, the

[1] http://www.scintitech.com/Support.aspx?MenuId=26&MainId=5, accessed 3/18/2015.