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Stability Measures for Rolling Schedules with Applications to Capacity Expansion Planning, Master Production Scheduling, and Lot Sizing

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Abstract

This contribution discusses the measurement of (in–)stability of finite horizon production planning when done on a rolling horizon basis. As examples we review strategic capacity expansion planning, tactical master production scheduling, and operational capacitated lot sizing.

Keywords: Rolling horizon, nervousness, rescheduling, capacity expansion, master production scheduling, lot sizing

1 Introduction

Planning methods with a finite horizon are, by definition, tailored to construct a plan for T periods. Consider, for instance, capacity expansion planning which is a long–term production planning problem. Since the lifetime of a firm is supposed to last beyond the planning horizon, capacity expansion planning is not a single event. A quick and dirty approach to meet that situation would be to plan for the T periods $1, \ldots, T$, to implement that plan, to plan for the next T periods $T+1, \ldots, 2T$, afterwards, and so on. This would make long–term production planning being a process running a solution method every T periods. Beside the fact that the final state of one production plan defines the initial state for the next, these runs would be independent.

In a real–world situation, however, this working principle would not be appropriate for several reasons. The capacity demand for instance appears to be non–deterministic. A more accurate estimate for capacity demand refines early forecast as time goes by, and (unexpected) events such as the invention of new technologies, process innovations, and competition issues make expansion plans obsolete.

So, what usually happens is that planning overlaps. This is to say that starting with a plan for the periods $1, \ldots, T$ the plan for the first, say $\Delta T \geq 1$, periods is implemented and a new plan is then generated for the periods $\Delta T + 1, \ldots, \Delta T + T$ which coins the name rolling horizon. In other words, the production in the periods $\Delta T + 1, \ldots, T$ is rescheduled. Note, if $\Delta T < \frac{T}{2}$ some periods are revised more than once.

This point of view reveals the capacity expansion planning problem with T periods being a subproblem in a rolling horizon implementation. While the first ΔT periods of the current plan are implemented, new expansion sizes may differ markedly from a former expansion plan in later periods due to rescheduling. This phenomenon is known as nervousness [3, 4, 8, 11, 12, 38, 48, 58, 61, 65, 67, 68]. Since many proceedings such as financial planning and subcontracting do heavily interact with the expansion process and the supply chain management is also affected by capacity expansion, nervous plans cause high transaction costs. It is unlikely to find methods which take all relevant aspects into account. Hence, the performance of capacity expansion planning methods should not only be evaluated by run–time and objective function values for a fixed horizon, but by cost and (in–)stability measures for the performance on a rolling horizon basis, too. This not only holds for the capacity expansion example, but for many other production planning problems, too.

To emphasize the relevance of this work, Section 2 discusses several production planning problems for which decisions are to be made on a rolling horizon basis. These examples range from capacity expansion planning which is a strategic (long–term) decision, to master production scheduling which is a tactical (medium–term) decision, to lot sizing which is an operational (short–term) decision. In Section 3 we review some more literature for planning in rolling horizon implementations. Stability measures are then suggested in Section 4. Section 5 is devoted to discuss the implications of robust planning to solution methods. Concluding remarks in Section 6 finish the paper.

2 Some Production Planning Problems

2.1 Capacity Expansion Planning

The problem of capacity expansion planning is to acquire extra capacity for a facility in order to meet a monotonically growing capacity demand. The finite planning horizon (which is typically several years) is subdivided into a number of discrete time periods (such as months). Capacity which is acquired before it is used incurs holding costs for carrying excess capacity. Expanding the capacity of a facility causes expansion costs. Furthermore, capacity that is available at one facility may be converted to be available at another facility. This raises conversion costs.

To give a mathematical programming model for capacity expansion planning (CEP), Table 1 defines the decision variables and Table 2 specifies the parameters.

Symbol	Definition
I_{jt}	Excess capacity at facility j at the end of period t.
q_{jt}	Capacity expansion at facility j in period t.
y_{jit}	Capacity conversion from facility j to facility i in period t .

Table 1: Decision Variables for CEP

$$\min \sum_{j=1}^{J} \sum_{t=1}^{T} (s_{jt}(q_{jt}) + h_{jt}(I_{jt}) + \sum_{\substack{i=1 \\ i \neq j}}^{J} c_{jit}(y_{jit})) \tag{1}$$

subject to

Symbol	Definition
c_{jit}	Conversion cost function for converting capacity at facility j to capacity at facility i in period t.
d_{jt}	Increment of demand for capacity at facility j in period t.
h_{jt}	Non–negative holding cost function for having excess capacity at facility j at the end of period t.
I_{j0}	Initial capacity at facility j.
J	Number of facilities.
s_{jt}	Non–negative expansion cost function at facility j in period t.
T	Number of periods.

Table 2: Parameters for CEP

$$I_{jt} = I_{j(t-1)} + q_{jt} + \sum_{\substack{i=1 \\ i \neq j}}^{J} y_{ijt} - \sum_{\substack{i=1 \\ i \neq j}}^{J} y_{jit} - d_{jt} \qquad \begin{array}{l} j = 1, \ldots, J \\ t = 1, \ldots, T \end{array} \qquad (2)$$

$$I_{jt} \geq 0 \qquad \begin{array}{l} j = 1, \ldots, J \\ t = 1, \ldots, T \end{array} \qquad (3)$$

$$y_{jit} \geq 0 \qquad \begin{array}{l} j, i = 1, \ldots, J \\ t = 1, \ldots, T \end{array} \qquad (4)$$

The objective (1) is to minimize the sum of expansion, holding and conversion costs. Equations (2) are the inventory balances. At the end of a period t the capacity at facility j is what was there at the end of period $t-1$ plus the capacity expansion at facility j in period t plus what is converted to facility j minus what is converted from facility j. (3) and (4) are simple non–negativity conditions.

Since the expansion, holding and conversion cost functions are usually assumed to be non–linear, the resulting model is not easy to solve. The above model formulation is discussed in [52]. For a variety of related models and methods we refer to [27, 32, 33, 35, 40, 54, 55, 56, 57, 69, 70].

2.2 Master Production Scheduling

The problem of master production scheduling is to schedule item families for production in order to meet some external demand without backlogs and stockouts. The finite planning horizon (which is typically less than two years) is subdivided into a number of discrete time periods (such as weeks or months). Item families share common resources, e.g. production units. The aggregated capacity of a production unit may vary over time. Producing one unit of an item family requires a family–specific amount of the available capacity. The capacity of a production unit may be exceeded by using a limited amount of overtime which incurs extra costs. Items which are produced in a period to meet some future demand must be stored in inventory and thus causes family-specific holding costs.

To give a mathematical programming model for master production scheduling (MPS), Table 3 defines the decision variables. Likewise, Table 4 provides the parameters.

Symbol	Definition
I_{jt}	Inventory for item family j at the end of period t.
O_{mt}	Overtime in production unit m in period t .
q_{jt}	Production quantity for item family j in period t.

Table 3: Decision Variables for MPS

Symbol	Definition
C_{mt}	Available capacity of the production unit m in period t.
d_{jt}	External demand for item family j in period t.
h_j	Non-negative holding cost function for item family j.
I_{j0}	Initial inventory for item family j.
J	Number of item families.
M	Number of production units.
o_{mt}	Non-negative overtime cost function for production unit m in period t.
O_{mt}^{max}	Upper bound for the overtime in production unit m in period t.
p_{jm}	Capacity needs in production unit m for producing one unit of item family j.
T	Number of periods.

Table 4: Parameters for MPS

$$\min \sum_{j=1}^{J} \sum_{t=1}^{T} h_j(I_{jt}) + \sum_{m=1}^{M} \sum_{t=1}^{T} o_{mt}(O_{mt}) \tag{5}$$

subject to

$$I_{jt} = I_{j(t-1)} + q_{jt} - d_{jt} \qquad \begin{array}{l} j = 1, \dots, J \\ t = 1, \dots, T \end{array} \tag{6}$$

$$\sum_{j=1}^{J} p_{jm} q_{jt} \leq C_{mt} + O_{mt} \qquad \begin{array}{l} m = 1, \dots, M \\ t = 1, \dots, T \end{array} \tag{7}$$

$$O_{mt} \leq O_{mt}^{max} \qquad \begin{array}{l} m = 1,\ldots,M \\ t = 1,\ldots,T \end{array} \qquad (8)$$

$$I_{jt}, q_{jt} \geq 0 \qquad \begin{array}{l} j = 1,\ldots,J \\ t = 1,\ldots,T \end{array} \qquad (9)$$

$$O_{mt} \geq 0 \qquad \begin{array}{l} m = 1,\ldots,M \\ t = 1,\ldots,T \end{array} \qquad (10)$$

The objective (5) is to minimize the sum of holding and overtime costs. Equations (6) are the inventory balances. At the end of a period t we have in inventory what was in there at the end of period $t-1$ plus what is produced minus external demand. Capacity constraints are formulated in (7). The amount of overtime is limited by (8). (9) and (10) are simple non-negativity conditions.

Usually, the holding cost and the overtime cost functions are assumed to be linear functions. The model formulation is then a linear program and is thus considered to be easy to solve without considering a rolling horizon. Models and methods for master production scheduling are discussed in [1, 34, 50, 74].

2.3 Lot Sizing

The problem of lot sizing is that several items are to be produced in order to meet some known (or estimated) dynamic demand without backlogs and stock-outs. The finite planning horizon (which is typically less than six months) is subdivided into a number of discrete time periods (such as hours, shifts, days, or weeks). Furthermore, items share a common machine. The scarce capacity of that machine may vary over time. Producing one item requires an item–specific amount of the available capacity. Items which are produced in a period to meet some future demand must be stored in inventory and thus cause item–specific holding costs. Production can only take place if a proper state is set up. Setting the machine up for producing a particular item incurs item–specific setup costs Setup times are to be considered, too.

To give a mathematical programming model for the capacitated lot sizing problem (CLSP), Table 5 defines the decision variables. Likewise, the parameters are explained in Table 6.

Symbol	Definition
I_{jt}	Inventory for item j at the end of period t.
q_{jt}	Production quantity for item j in period t.
x_{jt}	Binary variable which indicates whether a setup for item j occurs in period t ($x_{jt}=1$) or not ($x_{jt}=0$).

Table 5: Decision Variables for the CLSP

Symbol	Definition
C_t	Available capacity of the machine in period t.
d_{jt}	External demand for item j in period t.
h_j	Non–negative holding cost function for item j.
I_{j0}	Initial inventory for item j.
J	Number of items.
p_j	Capacity needs for producing one unit of item j.
sc_j	Non–negative setup cost function for item j.
st_j	Non–negative setup time for item j.
T	Number of periods.

Table 6: Parameters for the CLSP

$$\min \sum_{j=1}^{J} \sum_{t=1}^{T} (sc_j(x_{jt}) + h_j(I_{jt})) \tag{11}$$

subject to

$$I_{jt} = I_{j(t-1)} + q_{jt} - d_{jt} \qquad \begin{array}{l} j = 1, \ldots, J \\ t = 1, \ldots, T \end{array} \tag{12}$$

$$p_j q_{jt} \leq C_t x_{jt} \qquad \begin{array}{l} j = 1, \ldots, J \\ t = 1, \ldots, T \end{array} \tag{13}$$

$$\sum_{j=1}^{J} (p_j q_{jt} + st_j x_{jt}) \leq C_t \qquad t = 1, \ldots, T \tag{14}$$

$$x_{jt} \in \{0, 1\} \qquad \begin{array}{l} j = 1, \ldots, J \\ t = 1, \ldots, T \end{array} \tag{15}$$

$$I_{jt}, q_{jt} \geq 0 \qquad \begin{array}{l} j = 1, \ldots, J \\ t = 1, \ldots, T \end{array} \tag{16}$$

The objective (11) is to minimize the sum of setup and holding costs. Equations (12) are the inventory balances. At the end of a period t we have in inventory what was in there at the end of period $t - 1$ plus what is produced minus external demand. Due to (13) production can only take place if there is a proper setup state. Capacity constraints are formulated in (14). (15) define the binary–valued setup state variables, while (16) are simple non–negativity conditions. For letting inventory variables I_{jt} be non–negative backlogging cannot occur.

Usually, the setup and the holding cost functions are assumed to be linear functions which makes the model become amenable to mixed–integer programming methods. There is a huge amount of literature dealing with capacitated lot sizing. A comprehensive review is doomed to failure. We refer to [23, 26, 46, 68] for some state-of-the-art references based on the CLSP. A variety of other capacitated lot sizing models and methods can be found in [14, 24, 30, 31, 36, 37, 41, 42, 43, 44, 45, 64].

For the sake of simplicity, we use the terminology of lot sizing in subsequent sections. For example, the terms production quantity and lot size must be changed to expansion size for the capacity expansion problem, the term item stands for item family in the context of master production scheduling and for facility in the context of capacity expansion.

3 Literature Review

The question of how to measure the performance of a planning method when applied on a rolling horizon basis is discussed and studied by several authors. There are two main streams. Some authors consider cost oriented measures while others suggest stability oriented performance measures. If computational studies are done, a plan is generated for the periods $1, \ldots, T, \ldots, \hat{T}$ where $\hat{T}$ is a parameter of the test-bed. Note, this is an approximation, because the result for $\hat{T} \to \infty$ would be of interest.

In [2] the ratio of the objective function value of the implemented plan to the optimum objective function value of the overall problem for the periods $1, \ldots, T, \ldots, \hat{T}$ is considered. This value is greater than or equal to one where a value close to one is desired. Comparing several methods when applied on a rolling horizon basis can be done as in [21] where different methods are applied to the same instances and the objective function values of the implemented plans are compared.

A measure for instability is presented in [7] where $\Delta T = 1$ is assumed. Instability is expressed as the number of lots in the first period which are to be produced after a rescheduling operation but which were not scheduled before. Changes in the size of the lots are not considered. This measure is extended in [39] where those lots are counted as well which are not scheduled any more but which were before. Also, a measure which computes the changes of lot sizes in the first period is introduced. In both cases, a value close to zero indicates little changes. In [66] it is argued that focusing on the first period only and disregarding changes in the size of the lots is inappropriate. Thus, a measure is proposed which takes lot size changes in all periods into account.

Some other work is devoted to find out in what situations an extension of the planning horizon does not affect the plan in early periods [66]. In some cases, a so-called decision horizon $\check{T} < T$ can be determined. For example, see [5, 6, 9, 16, 17, 25, 28, 29, 47, 49, 53, 59, 73]. This means that an optimum solution for every instance with more than $\check{T}$ periods can be found such that the optimum solution for the subproblem consisting of periods $1, \ldots, \check{T}$ is a part of the overall optimum solution. In such a case, $\Delta T = \check{T}$ should be chosen.

The impact of the choice of T on the performance of methods for the Wagner–Whitin problem in a rolling horizon implementation is studied in [2, 10, 13, 15, 60, 63]. Surprisingly, choosing large values for T is not the best choice as one could have expected. A significant effect of forecast errors for demand on the performance is proven in [21, 20, 71]. Error bounds for implementing the plan in the first ΔT periods without having any information beyond period T are discussed in [18, 22, 28, 51].

Nervousness in the context of machine scheduling is discussed in [19, 72].

4 Stability Measures

To measure the performance of a production planning method when used with a rolling planning horizon, assume that a T–period subproblem is solved $n > 0$ times. As a result we get a production plan for the periods $1, \ldots, T, \ldots, \hat{T} = (n-1)\Delta T + T$. Following the lines above, in each run $i = 1, \ldots, n-1$ the plan for the periods $(i-1)\Delta T + 1, \ldots, i\Delta T$ is implemented while the plan for the periods $i\Delta T + 1, \ldots, (i-1)\Delta T + T$ is of a preliminary nature. Let

$$\dot{q}_j^{(i)} \stackrel{def}{=} \sum_{t=1}^{T-\Delta T} \zeta_{jt} q_{j(t+i\Delta T)} \tag{17}$$

for $i = 1, \ldots, n-1$ denote the weighted production quantities for item $j = 1, \ldots, J$ that are temporarily scheduled and let

$$\ddot{q}_j^{(i)} \stackrel{def}{=} \sum_{t=1}^{T-\Delta T} \zeta_{jt} q_{j(t+(i-1)\Delta T)} \tag{18}$$

for $i = 2, \ldots, n$ be the weighted production quantities for item $j = 1, \ldots, J$ after rescheduling in those periods which overlap. Note, the variables q_{jt} are defined for $t = 1, \ldots, T$ in preceding sections. It should be clear that when solving the i–th subproblem we have period indices $t = (i-1)\Delta T + 1, \ldots, (i-1)\Delta T + T$ and that without loss of generality a simple index transformation enables us to use the presented models as they are. The item–specific weights ζ_{jt} for $j = 1, \ldots, J$ and $t = 1, \ldots, T - \Delta T$ should be positive and non–increasing over time to take into account that changing the schedule in periods close to the planning horizon is not as bad as changing the schedule in periods close ahead. For example, one may use

$$\zeta_{jt} \stackrel{def}{=} \frac{1}{t} \tag{19}$$

for $j = 1, \ldots, J$ and $t = 1, \ldots, T - \Delta T$ which is item–independent and thus expresses that we have no preference to keep the schedule for some items more stable than the schedule for some others. Changes of a production plan due to rescheduling should be considered in relation to the total quantity that is scheduled. Hence, a stability measure for generating the production plan of item $j = 1, \ldots, J$ can be defined as the maximum instability

$$sm_j^{max} \stackrel{def}{=} \max\left\{ \frac{|\, \ddot{q}_j^{(i)} - \dot{q}_j^{(i-1)} \,|}{\max\{\ddot{q}_j^{(i)}, 1\}} \;|\; i = 2, \ldots, n \right\} \tag{20}$$

or the mean stability

$$sm_j^{mean} \stackrel{def}{=} \frac{1}{n-1} \sum_{i=2}^{n} \frac{|\, \ddot{q}_j^{(i)} - \dot{q}_j^{(i-1)} \,|}{\max\{\ddot{q}_j^{(i)}, 1\}}. \tag{21}$$

Values close to zero indicate a high stability in both cases. Since we face a multi–item problem, we wish to have a stability measure SM for the generation of an overall plan. Some possibilities are the maximum of the maximum instabilities

$$SM_{max}^{max} \stackrel{def}{=} \max\{sm_j^{max} \mid j = 1, \ldots, J\}, \tag{22}$$

the mean of the maximum instabilities

$$SM_{mean}^{max} \stackrel{def}{=} \frac{1}{J} \sum_{j=1}^{J} sm_j^{max}, \tag{23}$$

the maximum of the mean stabilities

$$SM_{max}^{mean} \stackrel{def}{=} \max\{sm_j^{mean} \mid j = 1, \ldots, J\}, \tag{24}$$

or the mean of the mean stabilities

$$SM_{mean}^{mean} \stackrel{def}{=} \frac{1}{J} \sum_{j=1}^{J} sm_j^{mean}. \tag{25}$$

In all cases, a value close to zero indicates good performance. A relation between these four performance measures is established by the following two inequalities:

$$SM_{mean}^{mean} \leq SM_{max}^{mean} \leq SM_{max}^{max} \tag{26}$$

$$SM_{mean}^{mean} \leq SM_{mean}^{max} \leq SM_{max}^{max} \tag{27}$$

Note, these performance measures are instability measures. Hence, if we would choose $\Delta T = T$, we would have no instability at all. There seems to be a trade–off between the stability of a plan and its cost performance in an ex post analysis. Hence, a cost oriented measure which compares the total costs of the implemented plan with (a lower bound of) the costs of an optimum overall plan that is generated under the assumption that all data for the periods $1, \ldots, \hat{T}$ are known in advance should be considered, too. Choosing a value ΔT that is used for planning is thus a bi–criteria optimization problem.

5 Implications to Planning Methods

The question that arises is how to take the stability of a plan into account when solving a production planning problem. Let $i \geq 2$ be the number of the run that is performed and

$$sm_j(i) \stackrel{def}{=} \frac{\mid \ddot{q}_j^{(i)} - \dot{q}_j^{(i-1)} \mid}{\max\{\ddot{q}_j^{(i)}, 1\}} \tag{28}$$

be an item–specific instability measure that is derived from (20) and (21), respectively, taking into account what run i can affect. Furthermore, let $SM(i) \in \{SM^{max}(i), SM^{mean}(i)\}$ be the overall (in-)stability measure under concern where

$$SM^{max}(i) \stackrel{def}{=} \max\{sm_j(i) \mid j = 1, \ldots, J\}, \tag{29}$$

and

$$SM^{mean}(i) \stackrel{def}{=} \frac{1}{J} \sum_{j=1}^{J} sm_j(i), \tag{30}$$

are measures derived from (22) through (25) by taking only into account again what run i can affect.

A first idea is to add a constraint of the form

$$SM(i) \leq \epsilon \tag{31}$$

to the model where ϵ is a user–defined parameter representing the maximum acceptable instability. This, however, is a non–linear constraint which makes mathematical programming approaches hard to implement. Using common sense heuristics will thus be a good piece of advice in such cases.

A probably better idea is to give up the idea of additional constraints and to consider a modified objective function. Let Z denote the objective function of the production planning problem. An idea would be to minimize either

$$Z \cdot SM(i) \tag{32}$$

or

$$Z + \alpha \cdot SM(i) \tag{33}$$

where $\alpha \geq 0$ is defined by the user for scaling and for weighting the stability criterion with respect to the (former) objective function value.

A third idea is to consider two objectives: Minimizing the objective function value and minimizing the instability. Methods for multi–criteria decision making [62], among them interactive procedures, are then applicable. Perhaps, this is the best idea, because existing heuristics could be used as submodules.

Finally, we will give a little discussion under which conditions robust scheduling is expected to work well.

Production planning usually has to take capacity limits into account. This is so for the master production scheduling and the lot sizing example given in earlier sections. Extended models of capacity expansion planning may also consider upper bounds for expansion sizes. If capacities are scarce, we do expect that finding a robust plan is easier than in uncapacitated cases, because the degree of freedom for rescheduling is smaller. This may turn out to be false, if even finding a feasible plan is a non–trivial task. This, for instance, is the case for lot sizing with positive setup times.

The examples that we considered in Section 2 could be classified as grouping problems, because there is a trade–off between grouping demands together versus fulfilling each demand separately. Thus, the ratio of the cost savings that are gained by grouping and the costs that are caused by grouping are important parameter settings. For lot sizing, for example, this is the ratio of setup and holding costs per item. It is expected that a high ratio is positively correlated with instability, because a low ratio tends to give production plans which are quite similar to the demand matrix.

6 Conclusion

We have discussed stability measures for dynamic production planning with rolling schedules. As examples we have given the long–term capacity expansion planning problem, the medium–term master production scheduling problem, and the short–term capacitated lot sizing problem. The (in–)stability measures that we propose take changes in all those periods into account which are rescheduled. The amount of change is also considered. Future work should put an emphasis on the development of methods including rescheduling for finding robust plans. A first step towards this goal is to figure out which problem parameter settings cause high instability.

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