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Production Planning by Pinch Analysis in Dynamic and Seasonal Markets

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In chemical engineering, pinch analysis holds a long tradition as a method for determining optimal target values for heat or mass exchanger networks by calculating an optimal alignment of available flows. A graphical representation of the time-material production relationship derived from the original pinch analysis can be used for aggregate production planning. This can deliver insights in the production planning problem as several production strategies can be compared. The approach is applied to a case study on bicycle coating. In this application, the dependence of the planning outcome on the starting season and the occurrence of stock-out using the pinch planning method were identified as shortcomings of the method for which solutions are proposed.

1. Introduction

The problem of planning the future production capacity of a company can be addressed in numerous ways and has been extensively discussed in literature. A good overview of standard methods is given in (Luss, 1982). For more recent approaches, the reviews of (Van Mieghem, 2003) and (Wu et al., 2005) are recommended, with the latter focusing on high-tech industries. When companies face a seasonal demand, the problem of capacity adaptation can become even more challenging, as there may be a constant need for capacity adaptations. Forecasting such seasonal demands is possible using various statistical methods, mostly aiming at identifying a seasonal component in historical demand data (see for example (Winters, 1960)). Given a prediction of the upcoming seasonal demand, a company still has to choose its production strategy, i.e., when to operate at which production rate. (Singhvi and Shenoy, 2002; Singhvi et al., 2004) propose a graphical method that represents demand and supply data as composite curves and derives inspiration of pinch analysis. This approach is a classical method from the chemical process industry that aims at optimizing a system's performance by analyzing the process streams, i.e. mass and energy flows, and possible interconnections. The same methodology can be applied to product streams and the time-material production relationship. The application of the analysis is shown for a bicycle company facing seasonal changes throughout the year and different production planning strategies are compared based on cost criteria.

2. Production Planning applying the Pinch Analysis Approach

2.1 The Classical Pinch Analysis for Heat Integration

The basic idea of the thermal pinch analysis is a systematic approach to the minimisation of lost energy in order to come as close as possible to a reversible system (see (Linnhoff et al., 1979; Geldermann et al., 2006b)). In its first step the pinch analysis yields the best possible heat recovery at the thermodynamic optimum. Thus, the pinch analysis requires the combination of hot and cold process streams to composite curves and the description of the respective temperature-enthalpy relationships. However, there exists a trade-off between the savings in operating costs for the hot utility and the investment in the heat exchanger. The result of the pinch analysis is the energy savings potential for the considered set of processes.

2.2 Translation of the Thermal Pinch Analysis to Production Planning

An analysis of intra- and inter-company production networks on the basis of product streams is also possible in analogy to the classical pinch analysis. *The time-material production* relationship can be used for a pinch analysis approach for aggregate production planning (Singhvi and Shenoy, 2002; Singhvi et al., 2004). Based on material balances, a time versus material quantity plot can be derived in translation of the original thermal pinch analysis (see Figure 1).

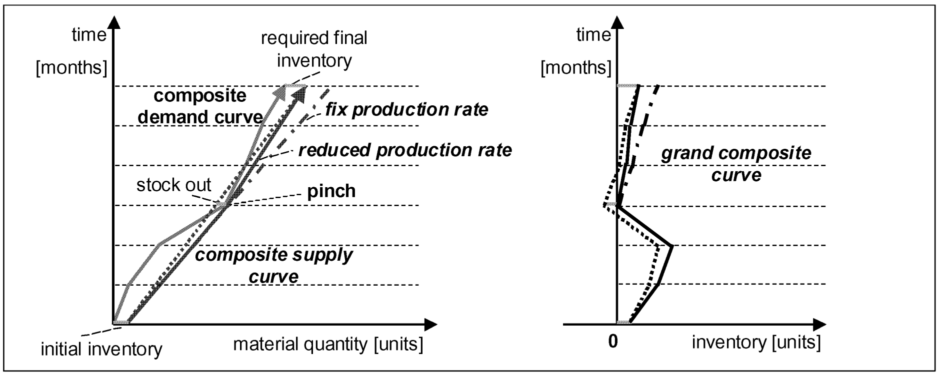

Figure 1: Production Planning (Singhvi and Shenoy, 2002)

The quality parameter in the production-planning pinch is the time of production (in analogy to the temperature level T). The quantity parameter is the demand of units to a certain time (in analogy to the enthalpy ΔH, describing the sum of internal energy of a thermodynamic system. One demand composite curve and one production composite curve can be constructed on a time basis (cf. Figure 1). In this context aggregated production planning is defined as the identification of an overall level of production for an individual company. The focus of the analysis is the evaluation of seasonal changes on the demand side and its consequences for setting the level of production during the whole period considered. The central issue in this case is how to choose and adapt the production rate during the period in order to avoid stock-outs and minimize inventory and capacity changes.

2.3 Discussion of Production Strategies

Different options for the level of production can be discussed based on costs, such as investment dependent costs, labour costs, material costs, inventory costs, stock-out penalty costs and costs for capacity adjustments (hiring and layoff costs). The strategies illustrate different ways based on flexibility and costs to comply with the demand composite curve and to supply the required aggregated demand (cf. Table 1).

Table 1: Regarded Production Strategies

Number	Strategy	Pinch Points	Capacity Adjustments	Stock-Outs allowed
1	Fixed Production Level with one Pinch Point	1	0	no
2	Variable Production Level with one Pinch Point	1	1	no
3	Variable Production Level with multiple Pinch Points	var.	var.	no
4	Average Production Level	0	0	yes
5	Max-Zero Strategy	0	1	no
6	Chase Strategy	var.	var.	no

Variable Production Level with one Pinch Point is the strategy derived from pinch analysis by (Singhvi and Shenoy, 2002; Singhvi et al., 2004). Whereas they find this strategy to deliver the same results as a standard linear optimisation based on cost assumptions for a specific example, the focus of this paper is its comparison with alternative production strategies concerning applicability and the quality of the results. This strategy consists of choosing the minimal production rate from the starting point that does not create stock-outs. The point where this straight line is tangent to the demand composite curve is called pinch point and the production rate is adapted here in break with its ending in the ending point required by the demand composite curve.
However, this strategy generated stock-outs for some demand patterns, especially if no ending inventory is planned. In case such stock-outs occur, we propose two corrective strategies: Firstly, the higher production rate before the pinch point could be maintained

for as many periods, as are needed in order to build up sufficient inventory levels. This solution increases inventory costs, but passes on additional adjustments of the production rate.

A second solution is strategy 3 called *Variable Production Level with multiple Pinch Points*, which foresees an adaptation of the production rate in several pinch points, determined as the point of contact of the minimal production rate below the demand composite curve, starting from the last pinch point. This strategy may entail several adaptations of the production rate, however only in cases where the one pinch point strategy leads to stock-outs. As this strategy is viable for most given demand patterns, it was superior to the other strategies in most cases. This strategy could be further enhanced, for example by considering the trade-off between stock-outs, inventory and capacity adaptations for every pinch point. The *Average Production, Max-Zero* and the *Chase strategy* are used as benchmarks for the evaluation of the trade-off of the penalty for stock-outs on the one hand and the inventory costs on the other.

Challenge for the analysis is the determination of the starting time interval for the analysis. In contrast to the thermal pinch analysis in which all heating and cooling requirements are sorted according to their quality parameter temperature and resulting a theoretical minimal utility target, the sorting of the demand in the production pinch analysis is infeasible. Consequently, the analysis can result in sub-optimal solutions and the results significantly alter depending on the selected starting interval. Here, we propose the beginning of the peak season, which means the highest growth rates, as the starting point of the evaluation. However, more research is needed here in order to provide recommendations for arbitrary demand lines.

2.4 Case Study

In the following the bicycle production of a reference company is taken into account (see (Geldermann et al., 2006)) and a distribution of the demand throughout the year is assumed according to Table 2. Five basic strategies for production planning are discussed (cf. Table 1) here. Since the seasonal increase of demand starts in October it is the starting month of the evaluation. Table 2 shows the demand for each regarded month and the corresponding production rate according to the five applied strategies discussed below. The costs of each production strategy are calculated using estimated values for material, labour and inventory. This calculation is done in a similar way as in (Singhvi and Shenoy, 2002; Singhvi et al., 2004), however they use these assumed costs for a linear optimisation and compare the result to the pinch strategy, whereas here the resulting costs of different strategies are compared.

The relevant costs for choosing the production strategy in this basic calculation are hiring and layoff costs on one hand and inventory and stock-out costs on the other hand. As the latter two costs favour frequent changes in the production rate (only determined by the workforce in this case) and the first two punish such changes of the production rate (equal to the production capacity in this case), the pinch-inspired setting of the production rate is used to find a compromise. In this specific example, the strategies inspired by pinch analysis result in minimal costs, meaning they offer the best compromise between the objectives of low inventory/stock-out and a small number of costly capacity adaptations.

Table 2: Monthly Production Rates and Estimated Costs for all Strategies

<table>
<tr><th colspan="2" rowspan="2">Demand</th><th colspan="6">Production Rates [Bikes/Month]</th></tr>
<tr><th>Fixed Production with one Pinch-Point</th><th>Variable Production with one Pinch-Point</th><th>Variable Production, multiple Pinch-Points</th><th>Average Production Level</th><th>Max-Zero Strategy</th><th>Chase Strategy</th></tr>
<tr><td>October</td><td>90.000</td><td rowspan="12">108.000</td><td rowspan="7">108.000</td><td rowspan="5">108.000</td><td rowspan="12">83.333</td><td rowspan="6">166.667</td><td>90.000</td></tr>
<tr><td>November</td><td>90.000</td><td>90.000</td></tr>
<tr><td>December</td><td>110.000</td><td>110.000</td></tr>
<tr><td>January</td><td>130.000</td><td>130.000</td></tr>
<tr><td>February</td><td>120.000</td><td>120.000</td></tr>
<tr><td>March</td><td>90.000</td><td>90.000</td><td>90.000</td></tr>
<tr><td>April</td><td>80.000</td><td>80.000</td><td rowspan="6">0</td><td>80.000</td></tr>
<tr><td>May</td><td>60.000</td><td rowspan="5">48.800</td><td>60.000</td><td>60.000</td></tr>
<tr><td>June</td><td>50.000</td><td>50.000</td><td>50.000</td></tr>
<tr><td>July</td><td>50.000</td><td>50.000</td><td>50.000</td></tr>
<tr><td>August</td><td>60.000</td><td>60.000</td><td>60.000</td></tr>
<tr><td>September</td><td>70.000</td><td>70.000</td><td>70.000</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td colspan="2">Annual Cost [Thousands €]</td><td>30.918</td><td>22.539</td><td>21.702</td><td>23.465*</td><td>37.892</td><td>22.816</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td colspan="2">Ending Inventory [Bikes]</td><td>296.000</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
</table>

However, the *Variable Production Level with one Pinch Point* strategy generated stock-outs for some demand patterns, especially if no ending inventory is planned. In case such stock-outs occur, we propose two corrective strategies: Firstly, the higher production rate before the pinch point could be maintained for as many periods, as are needed in order to build up sufficient inventory levels. This solution increases inventory costs, but does not require additional adjustments of the production rate. As a further solution to eliminate the problem of stock-outs for the pinch strategy we propose a strategy called *Variable Production Level with multiple Pinch Points*, which is based on adapting the production rate in several pinch points, determined as the point of contact of the minimal production rate below the demand composite curve, starting from the last pinch point. This strategy may entail several adaptations to the production rate, however only in cases where the one pinch point strategy leads to stock-outs. As this strategy is viable for most given demand patterns, it was superior to the other strategies in most cases. This strategy could be further enhanced, for example by considering the trade-off between stock-outs, inventory and capacity adaptations for every pinch point. However, the determination of the starting time interval of the evaluation highly influences the results of the analysis. For the analysis the beginning of the peak season is proposed as the starting interval of the analysis. More comprehensive research concerning the time-variance of the results is necessary.

Compared to standard OR-methods like a linear optimisation based on a mathematical model of the total costs, the applicability of this basic graphical heuristic is limited to suited demand patterns and the optimality of results is not guaranteed. However, this model requires no detailed analysis of single cost factors and can thus ease the understanding and planning of production levels facing seasonal demand. Thus, an easy to use implementation of the method possibly allowing for including forecasting methods and multi-period planning for considering dynamic growth could be a valuable tool especially for small enterprises that generally do not use mathematical methods for production planning.

3. Conclusions

The application of the pinch analysis methodology to production planning provides a simple but effective tool for analysing production strategies of a company facing seasonal demand. Based on the cost parameters, different production strategies can be evaluated, those based on pinch analysis provide a good compromise between inventory costs and capacity adaptation costs. The basic idea by (Singhvi and Shenoy, 2002; Singhvi et al., 2004) has been improved by an opening step comprising the choice of a beginning period with the highest demands. Moreover, different strategies have been introduced. The idea to select a strategy with multiple pinch points was proposed in order to overcome stock-outs possible in the one pinch point strategy. Especially this strategy seems to be promising. Further investigations are necessary as regards the shape of the demand curves suited for the application of this method. The concept of graphically analysing the planning situation for identifying suited heuristics as those inspired by pinch analysis could be further transferred to planning the use or treatment of seasonally accruing material flows as for example in the field of biomass use or waste processing.

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