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Analyzing the relationship between manufacturing lead-times and line flexibility – the Line Flexibility Model

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Abstract

The Line Flexibility Model is developed to perform queuing analysis to address the benefits of line flexibility on lead-time for multi-product plants. It has successfully been applied to a case study at General Electrics' Flexible Compounding Plant in Bergen op Zoom. Based on historic order information, the relationship between line flexibility, system utilization and lead-time were quantified. Also, an estimate of productivity loss and its impact on lead-time were made. This information supported plant management to decide on the needed flexibility level, at different levels of system utilization. The model's main advantage is the ability to analyze the relationships between manufacturing capabilities and on-time delivery performance, independently of a specific scheduling approach.

Keywords: manufacturing flexibility, line flexibility, manufacturing lead-time

1. Introduction

Over the last decade, market conditions in many multi-product process industries have changed. Traditionally, these were characterized by price competition, leading to an emphasis on production efficiency and cost reduction. Today, however, many firms have chosen to compete on customer service. An important competitive asset is the ability of achieving short lead-times. Short lead-times however are hard to achieve in these industries due to technical (fixed, often dedicated production capacity) and market (demand unpredictability) characteristics.

Several options can be employed to achieve lead-time reduction. One of them is line flexibility, i.e. the capability, within a line-structured plant layout, of producing products of a certain type on more than one line. Applying the concept of line flexibility to the multi-product process industry may mean that more heterogeneous products are produced on one line, leading to longer setup times and hence loss of production capacity. The need to quantify the benefits and drawbacks of line flexibility calls for the development of a quantitative model. This paper presents such a model, called the Line Flexibility Model. It was developed for a General Electric Plastics compounding plant (Klompenhouwer, 2006) to answer the following question: How can multi-product enterprises best utilize the available capacity to meet variation in demand with good on-time delivery performance?

2. Line flexibility

Lead-time is generally defined as the time between the placement of an order and its fulfillment.

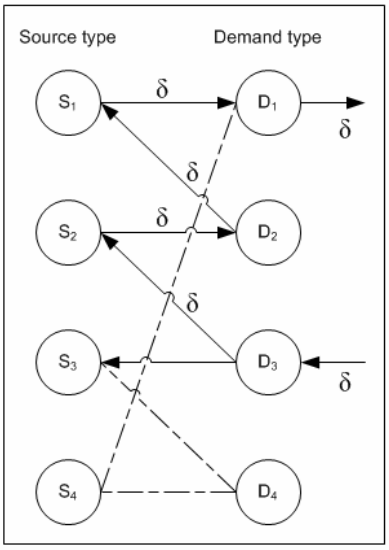

Figure 1. Structural flexibility. Source: Iravani et al., 2005.

Products are delivered late when the times required to manufacture and deliver products (actual lead-times) are longer than the lead-times as requested by the customer. Lead-time can be decomposed into several components. One of these components is manufacturing lead-time, which refers to the time spent in manufacturing, i.e. waiting time before production, production time, intermediate waiting time between processing steps, etc. In a turbulent market, it is a great asset for firms to sustain short lead-times despite unpredictable changes in demand. To achieve this, firms can consider employing flexible manufacturing solutions such as line flexibility.

Line flexibility is a promising flexible manufacturing solution for so-called flowshops, i.e. plants organized in production lines.

It refers to the capability of producing products of a certain type on more than one line, rather thandedicating each line to a preferred product group. The

concept of line flexibility is an instance of what Iravani *et al.* (2005) term structural flexibility: 'the ability of a system, provided by its structure of multicapability sources, to reallocate production to respond to changes in demand'.
Structural flexibility configurations are represented as links between products types and supply types. If variation in demand types occurs, demand can only be met by allowing the excess capacity for one demand type to be used to balance the lack of capacity for another demand type. As can be seen in Figure 1, excess demand for product D3 can be allocated to S2. Any excess demand for D2 resulting from this shift can be transferred to S1. Iravani *et al.* (2005) use the principle of chaining, as introduced by Jordan and Graves (1994), who argue that through the concept of chaining, the benefits of total flexibility can be achieved at lower levels of flexibility.

3. Line Flexibility Model

The relationship between line flexibility and waiting time can be viewed as a queuing problem. The queuing model developed here is based on discrete-event simulation and built in Arena. Figure 2 presents a high-level overview of the Line Flexibility Model's overall logic. It consists of several modules. The modules marked in grey are company-specific, depending on scheduling rules employed by the plant in question. 'Simulate batch arrival' concerns the creation of batches and the assignment of properties. Batch arrival can be simulated in two ways. Either a historic set of orders is read into the model or order arrival is simulated by creating a batch based on user-specified interarrival times.

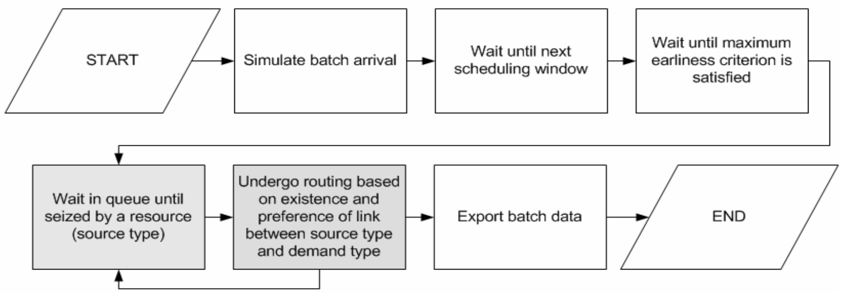

Figure 2. Overall logic of Line Flexibility Model: flow of batches through the simulation.

'Wait until next scheduling window' applies to plants where orders cannot be scheduled immediately upon order arrival. Orders are held in a queue upon order arrival and are released upon the start of a new scheduling period. 'Wait until maximum earliness criterion is satisfied' applies to plants that use a rule indicating that orders can be scheduled early up to a maximum. The implementation of 'Wait in queue until seized by resource' depends on the scheduling rules in place. For the case study described below, two queues were used, each with their own queue discipline: a queue for early orders (least early first) and a queue for on-time or late orders (earliest order entry first). Since not all batches can be produced on all lines with the same preference, the module ‘Undergo routing’ was developed. This module is dependent on the scheduling rules and on the line flexibility configuration. The algorithm is company-specific, see Figure 3. The goal of lead-time reduction is to improve customer satisfaction, i.e. to have the ability of delivering orders as fast as customer’s request. Therefore, besides lead-time, a second performance indicator was used: batch tardiness. Tardiness is simply measured, but measuring lead-times is less straightforward. Therefore, actual lead-time is measured only with orders with a requested lead-time of zero days. Their complete waiting time is explained by the fact that they have to wait for free capacity. The time that elapses between order entry and completion time is therefore used as a proxy for actual lead-time. To enable a reliable estimate, the model generates diagnostic or virtual orders at regular time intervals. These do not influence the tardiness metric, since they do not claim capacity on the production line. Their sole function is to diagnose how fast orders with short requested lead-times can be accommodated.

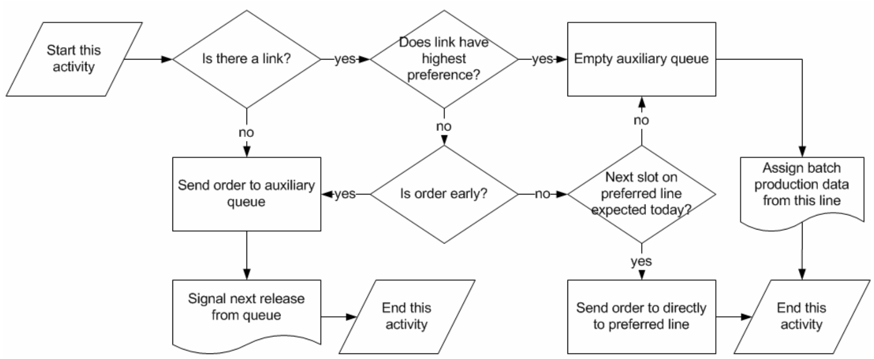

Figure 3. Queuing system logic: module ‘Undergo routing’.

4. Case study: General Electric Plastics’ Flexible Compounding Plant

The Line Flexibility model was developed for General Electric Plastics’ Flexible Compounding Plant (FCP) with the objective to quantify the impacts of line flexibility on lead-time, at different utilization levels. The plant transforms basic polymer powder into ready-to-use pelletized polymer material for a variety of industries. The product portfolio is composed of hundreds of different products, both make-to-order and make-to-stock. FCP’s products are grouped into ten product groups. The FCP plant consists of eight production lines, each of them dedicated to a number of product groups. When more than one line is made available to a certain product group, different preferences can be attached. A number of characteristics of FCP are worth mentioning:

1) Variable requested lead-times and variable batch sizes;
2) Sequence-dependent setup times (setup times may vary between flexibility configurations; this input parameter must be carefully specified);
3) Backordering (rather than simply refusing orders if they cannot be produced in time, the possibility exists to produce them late);
4) Possibility of early production when there is sufficient capacity available;
5) Wester *et al.* (1992) distinguish between three types of order acceptance approaches: *monolithic* (based on a detailed schedule), *hierarchical* and *myopic*. FCP uses the monolithic approach.

The model was applied using a large set of historical orders. One important finding was the criticality of the maximum earliness rule. The possibility of producing orders early prevents higher loading in the future. Thus, uneven capacity requirements between product groups over time are smoothed, alleviating part of the need for line flexibility. The impact of the maximum earliness rule depends on utilization and the requested lead-time mix of orders (many orders with short requested lead-times means that opportunities for early scheduling are limited). Fig. 4 presents the effect of more line flexibility on lead-time.

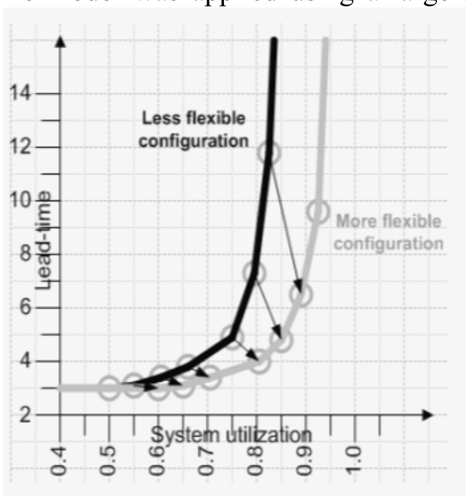

Figure 4: Effect of line flexibility on lead-time.

Line flexibility has most impact at high utilization levels. More line flexibility has the effect of spreading the order load at a given time over lines. A lack of line flexibility causes a rise in lead-time when subgroups' average loading is uneven, and when the product mix varies. In the less flexible situation (the black curve), lead-time increases for some of the product groups, while for others the lead-time is still low. In the more flexible situation (the grey curve), lead-time is more or less the same for all product groups. It can be concluded that the researched line flexibility configuration comes very close in on-time delivery performance to a situation of full flexibility. The downside of line flexibility in case of sequence-dependent setup times is that it can harm productivity. In Fig. 4, moving from one curve to the other encompasses a move downwards (shorter lead-time), and to the right (loss of productivity) (see the arrows in Fig. 4). Therefore, most benefits of line flexibility are expected at a limited, intelligently configured level of flexibility, rather than complete flexibility. This supports the findings of Chan et al. (2005), who also conclude that flexibility above a certain level becomes counter-productive. What the Line Flexibility Model adds is that it allows quantifying at which point flexibility becomes counter-productive. This information can support plant management to decide on the needed level of flexibility, at different levels of system utilization.

5. Discussion

The Line Flexibility Model was developed to perform queuing analysis to address the benefits of line flexibility on on-time delivery performance for multi-product plants in the process industry. This has successfully been applied to a plant with flowshop scheduling. Industries using multi-purpose equipment in various routings, with or without no-wait scheduling constraints, can also use the approach, albeit with some modifications in model logic (e.g. the addition of queues for intermediates). The model can thus be extended to become a Structural Flexibility Model. The Line Flexibility Model was used here to analyze the benefits of line flexibility in terms of on-time delivery performance. It can also be used to answer other types of questions, such as the impact on on-time delivery performance of using different priority rules. The Line Flexibility model is myopic in nature, while many enterprises use hierarchical or monolithic approaches. The Line Flexibility model allows for analyzing the manufacturing capabilities independent of the specific scheduling. Model outcomes should therefore not be treated as a prediction of future schedules.
Finally, it should be added that the Line Flexibility Model can interact with a planning model, so that conventional solutions, e.g. inventory management and batch sizing, can be studied. This would require combining the existing discrete event model with a model for the continuous paradigm.

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