REVERSE-TIME SIMULATION IN PRODUCTION LINE REDESIGN

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ABSTRACT

Reverse-time simulation in combination with straightforward simulation was applied to support the design of an assembly line of a series of complex products. These products had been completely redesigned in order to obtain "kanban" controlled "Just In Time" production and to minimize intermediate stocks. A buffer with universal subassemblies decouples anonymous "production to stock" and client specific "production to order". Simulation models are made of both pre and after decoupling buffer processes to study the dynamics of the assembly processes, to determine the decoupling buffer size and to develop rules for assigning personnel to assembly jobs. Currently new production lines have been installed and are in the initial start up phase.

INTRODUCTION

The combination of fast growing variety of client specific products and the customer demand for short product lead times and just in time delivery put great demands on production facilities. A well-known remedy for this problem is to shift the point at which production shifts from "Make to Stock" into "Make to Order", upstream of the production sequence. This point is called the "Client-order Decoupling Point" (van Goor, 1990). The "make to stock" departments preferably produce universal parts and sub assemblies. The "make to order" trajectory usually deals with type-specific or client-specific final products. If the lead-time in the make to order part of the line is too large then one is forced to produce or assemble on the basis of sales predictions instead of actual orders. Undesirable consequences of such a working method are large intermediate stocks as well as production overcapacity and often outdated parts or products.

Instead of shifting the Client-Order Decoupling Point upstream, a rigorous but very effective approach is to completely re-design the product range. The key issue then is to keep parts and sub-assemblies in the line anonymous or non-specific as far as possible downstream. The type-specific or client-specific features should be added as late and as fast as possible at the very end of the assembly line in order to obtain very short final product lead-times. A buffer with anonymous sub assemblies decouples both stages.

The objective of the project discussed in this paper is the design of the production line for a set of fully redesigned complex products. The actual product redesign process is not part of the paper. The paper focuses on the dynamics of the production before and after the decoupling buffer and the dimensioning of the buffer. The main issue is to get hold on the dynamics of the assembly line and the buffer size required as a function of variations in individual assemble job duration and irregularities in customer demand. In the modeling straightforward as well as reverse-time simulation is applied.

Reverse-time simulation already has been applied in Job Shop scheduling. The basic idea is to start jobs at their due dates and to simulate their reversed job routes. The Job Completion Times of the jobs are then used as job release times. (Mejtsky, 1985). A bi-directional simulation algorithm in which a number of alternately forward and reversed runs provide feasible job release times was proposed also in the field of job shop scheduling. (Chen-Tsau and Clark, 1994). Bi-directional simulation was further applied in stochastic network planning. (Ottjes, Veeke, 2000).

In this paper straightforward simulation was used for the assembly line before the decoupling buffer and to determine output characteristics of the line as a function of a number of variables. The variation in buffer size was determined applying reverse-time simulation on the total line.

CASE DESCRIPTION

The product range covers five main products in dispensing and mixing equipment for the paint and ink industry, each appearing in several hundreds of variants. Parts and sub-assemblies are made in a job shop or are purchased.

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Former production process:

In the former production process cell production was applied in which, in each production cell, one mechanic assembles a complete product from bottom to top, packing included. A cell was supplied from the pre-assembly departments with parts and substructures that were already mostly client specific. As a result of the growing diversity of product types this way of working caused increasing product lead times and introduced intermediate stocks and "not-value-adding" activities. Current lead-time for example is 6 weeks. Another disadvantage of such a situation is the rather restricted flexibility of production volume and product types.

New production process

The new product design has been set up modular and standardized to a great degree. The "client-order decoupling point" or the stage in which a product becomes client specific, is shifted as far as possible to the end of the assembly chain. The assembly steps before the decoupling buffer take place anonymous in a sequence of working stations in line. The resulting universal products are stored in the decoupling buffer. The number of working stations and duration of the assembly tasks are determined by the product design. The actual assembly steps are performed by mechanics. A mechanic assembles a complete product for the decoupling buffer step by step along the working stations. Each working station owns a set of special tools needed for its assembly step. At the start of an assembly sequence a mechanic obtains a cart with all parts and subassemblies needed for the product to be assembled. The carts are provisioned from preceding departments or via external suppliers according the "kanban" principle controlled by the needs derived from the decoupling buffer. Kanban control is introduced throughout the entire production. The number of active mechanics is equal or less than the number of working stations and depends onthe production volume required.

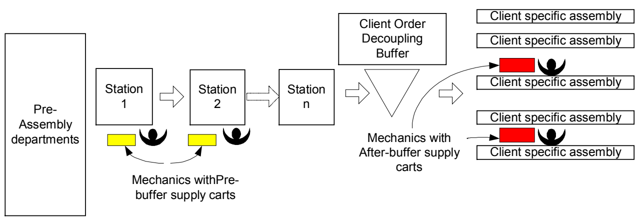

Figure 1. The total assembly line. Universal intermediate products are stored in the decoupling buffer. Client orders are assembled from this buffer in the after-buffer final assembly stations. Assembly workers may be exchanged between pre- and after-buffer assembly stations, controlled by the order status and the contents of the buffer

The number of final assembly activities per product after the decoupling buffer is minimized thanks to the new product design, still it amounts more than 100 assembly handlings per product taking some 3 hours in the average. The assembly steps in that area are client-order driven and client-specific. The final assembly stations are operating in parallel. A cart with all specific parts to complete a final product provides the part supply for a station. In figure 1 the production line arrangement is shown schematically.

MODELING

The models developed are implemented in the simulation package TOMAS (Tool for Object-oriented Modeling And Simulation), based on Delphi or C++ (Veeke, Ottjes, 2000, 2002). TOMAS supports the process interaction approach

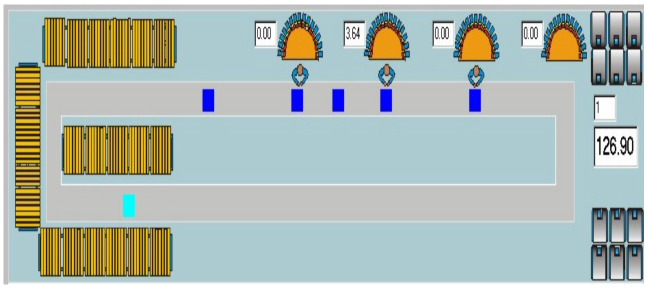

Figure 2. Animation screen of the pre-buffer model with 4 working stations and 3 mechanics. The pre-buffer assembly is split up in four steps. Each product is completed by one mechanic who steps along the working stations. The parts are supplied in one cart for each product. On the left side the loading of the assembly carts is represented.

as defined by Zeigler, (Zeigler et al. 2000). The process interaction worldview breaks down into two views corresponding to a different assumption as to what are active and passive elements in systems to be modeled. In the prototypical process interaction worldview the active elements are taken to be entities that do the processing, e.g. the mechanics etc.

Applying the process-interaction modeling can be summarized in three steps: Decomposition of the system into relevant classes of elements preferably patterned on the real-world elements of the system. Identification of the attributes of each element class and distinguishing the "living" element classes and provide their process descriptions. A process governs the dynamic behavior of each element.

We will give limited descriptions of the main element classes and their processes.

PRE-BUFFER MODEL

The pre-buffer model is made to determine the influence of several variables on the pre-buffer cycle time and to derive production characteristics such as production rate as a function of the number of pre-buffer mechanics and the number of working stations and the variation in the assembly time per working station. The characteristics will be used in the reverse-time model of the total line.

Variables are the number of assembly steps (stations), the number of mechanics in the line and the statistics of the individual station assembly times. The average time needed per assembly step should be equal for each station. The number of mechanics needed depends on the product flow required.

The main element class in the pre-buffer model is the class of mechanics. The process description of the class mechanic is:

```
Loop:
        Wait for a filled assembly cart
        For each working station starting with the first one
        Do:
                Wait until station is free
                Occupy station
                Draw assembly time from step time
                distribution
                Work assembly time on the station
                Free station
        Put assembled universal product in decoupling buffer
```

Here "Wait" and "Work" are so called "time-consuming" statements. With this model the dynamics of the pre-buffer line are investigated for one of the five product types. As the average pre-buffer cycle time of this product was designed to be 120 minutes the average time per working

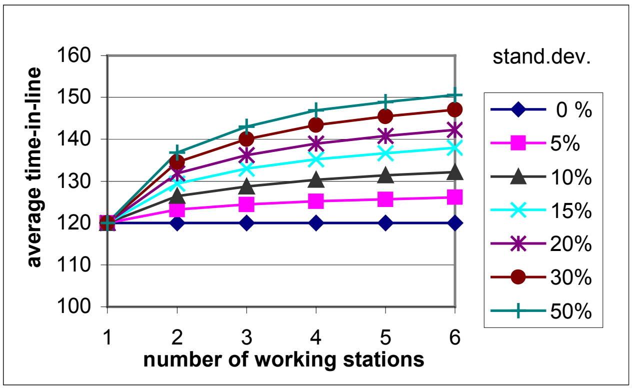

Figure 3: Average time-in-line as a function of number of working stations (=number of mechanics) in the line and the standard deviation per assembly step.

station called step time is $t_s = 120/n_w$ Here n_w is the number of working stations. The actual time per step in the model is drawn from a step time distribution with average t_s and a standard deviation varied as a percentage of t_s. If a sample falls outside a 33% range around the average it is set to this border value. First the influence of step time variations on the average time-in-line of a product was determined. Figure 3 shows the average time-in-line as a function of the number of working stations and the variation of the step time. The variations to be expected in reality are not known yet but are expected to be smaller than 10% and probably will diminish by the learning effect if the line is in use for some time. In case of 10% variation the average time-in-line is 132 min. In practice the production volume will determine the number of mechanics needed and the number of working stations should be equal or greater than the number of mechanics. In figure 4 the average time-in-line is shown as a function of the number of mechanics and the number of working stations. It appears to be advantageous to have more working stations than mechanics, as could be expected. Moreover a working station surplus allows flexibility with respect to production volume.

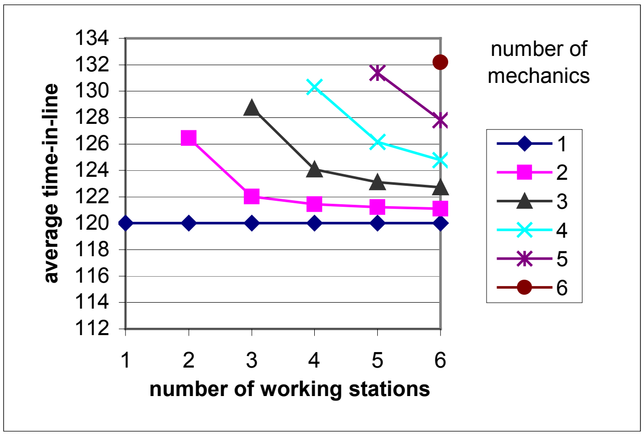

Figure 4: Average time-in-line as a function of number of working stations in the line and the number of mechanics assigned to the line. The standard deviation per step is 10 % of the average step time

REVERSE-TIME MODEL

In the after decoupling buffer model we used the technique of "reverse-time" simulation. The finished product is "disassembled" into its original sub-assemblies and these are stored in the decoupling buffer. The buffer is then discharged by the pre-buffer assembly line working in reverse direction. The real time in system t is obtained applying a time transformation according

$$t = t_0 - t_r$$

Here t_0 is the latest due date of the ordered products and t_r the time in the reverse simulated system.

In that way a production course is obtained guarantying just in time product completion. The difference with the traditional MRP approach is that in the model the proper assembly times are used and additional waiting times are determined in the model.

The development of the contents of the decoupling buffer is obtained by continuing the reverse simulation in the pre-buffer line. This was realized by simply emptying the buffer using the pre-buffer line characteristics obtained from the pre-buffer model. In the combined model rules are tested to exchange mechanics between pre- and after-buffer operations, depending of buffer status and current client orders.

The main element classes in the final reverse-time model are class *mechanic*, class *controller* and class *remover* the latter representing the reverse pre-buffer processes. A mechanic "disassembles" final products and puts the remaining universal substructures in the decoupling buffer. The Controller monitors the status of the total line and decides on exchanging mechanics between pre- and after-buffer production. The Remover is an aggregation of the reverse pre-buffer processes and removes products from the buffer in a rate corresponding to the number of mechanics that are assigned to the pre-buffer line. This rate is determined with the pre-buffer model discussed.

The products to be broken down for the "current" day are put into the "Breakdownlist". At the start of a new day the mechanics are re-assigned to pre- or after-buffer sections by the Controller. In order to minimize the buffer contents rules are needed to shift mechanics between pre- and after-buffer assembly tasks.

```
// After decoupling buffer Mechanic process

While Work in Breakdownlist > x do              1)
        Take first product from BreakDownList
        Work break down time
        Put resulting "stripped" product in buffer
Wait cycle time of Remover 2)
Join Remover Crew and update Remover Cycle time

//Process of Remover
Loop
        While buffer not empty do
                Remove first product from the buffer
                Wait current step time (depends on number
                of mechanics in Crew)
        Wait while buffer is empty
        Register waiting time 3)

//Process of Controller
Loop
        Fill Breakdownlist for next day including the
        remainder of the previous periods.
        Assign mechanics to pre- and after-buffer lines
        Start after-buffer mechanics
        Start remover
        Wait 1 day
```

1): **x** is a control variable and its value depends on the time needed to complete all jobs in the Breakdownlist and the number of mechanics in the after-buffer line

2): if a mechanic joins the remover it will take one cycle time before his contribution to the Remover cycle time becomes effective.

3): Waiting times can be interpreted as unproductive time. Mechanics stop working if the buffer has reached its predefined maximum contents.

EXPERIMENTS

The model is used to obtain insight in the line dimensions such as number of working stations before and after the decoupling buffer, the required buffer contents, the criteria to shift mechanics between pre- and after-buffer line and the flexible deploying of extra mechanics.

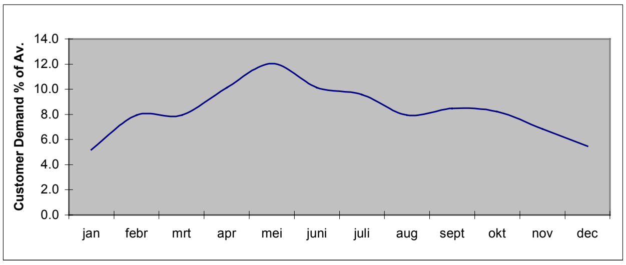

Figure 5: Relative customer demand pattern of all product types over one year

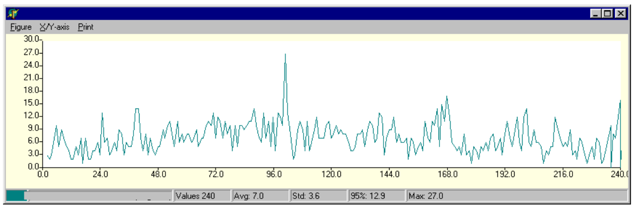

Figure 6: Customer demand for one of the five product types per day over one year of 240 working days

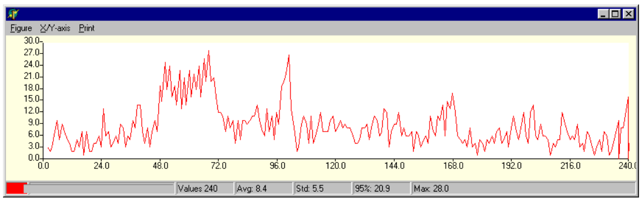

Figure 7: contents of Breakdownlist during a reverse time simulation run of 240 working days, starting at day 240

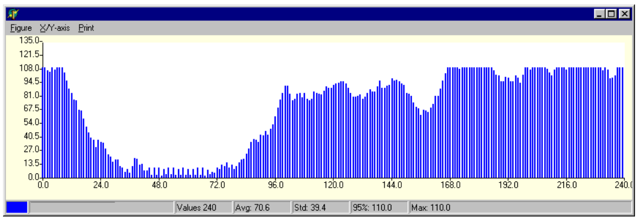

Figure 8: Contents of the decoupling buffer with a fixed number of 4 mechanics during 240 working days derived from a reverse time simulation run

As a basis the customer demand pattern of 2001 was used. Figure 5 shows a typical customer demand pattern over one year. This pattern is used to construct the input for the reversed time simulation runs. Figure 6 shows a typical customer demand pattern on a daily basis distributed over 48 weeks of five working days each. This input is used for

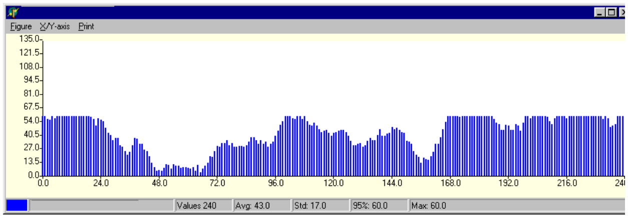

Figure 9: Contents of the decoupling buffer with 4 permanent mechanics and 1 extra mechanic during week 16- 24 in the peak period derived from a reverse time simulation run.

reverse-time simulation runs starting with the demand on day 240, working backwards and breaking down the products into the decoupling buffer. The Breakdownlist is filled up every day. Its development is shown in figure 7. In that figure a build up is observed from day 72 down to day 48 that is caused by a lack of remover capacity in that period. In the real time production situation this means that the production capacity in the pre-buffer zone cannot keep pace with the required output flow. This situation leads to non-performance with respect to just in time delivery. Figure 8 shows the accompanying buffer contents as a function of time. The contents was monitored during the reverse-time run but transformed into the real time buffer contents. Starting from arbitrary initial buffer contents the actual buffer contents is determined by subtracting the products that are "disassembled" at the after-buffer side from the initial buffer contents. In the case represented in figure 8, a series of runs varying the initial buffer contents, pointed out that an initial stock of 135 products guaranties just in time production over the whole period. So in the observed period employing 4 mechanics proved to be adequate to maintain production. The volume flexibility required by the imposed demand pattern is realized with an evenly balanced workload of the personnel. Figure 9 shows the result of a simulation run in which during a peak period one extra mechanic is deployed. This results in maximum contents of some 55 products in the decoupling buffer. In the real situation the costs of an extra mechanic and of an increased buffer contents have to be compared to each other.

Type flexibility is defined as the variation of types of each main product that can be delivered. In this simulation study only one of the five main product types has been concerned. However as all product types have been redesigned in the same way, the results for one line can be applied on the total product range. Only the number of lines has to be increased as well as the number of working stations in the after-buffer section. Type flexibility is obtained because all product types can be produced at any pre-buffer line and can be finished on any after-buffer working station.

CONCLUSIONS

Reverse-time simulation appears to be a useful approach to get insight in the buffer capacity required for decoupling anonymous production and client specific production. The influence of volume- and type-flexibility on the buffer limit was determined. Using historical production data for the simulation experiments provides very realistic data to be used in the production line design process. The models have been used to investigate rules for the dynamic re-assignment of mechanics between both pre- and after-buffer production. As a result of an installed surplus of working stations it's easy to increase production capacity by just adding or removing mechanics. The flexibility of production volume increases by temporary increasing the number of mechanics or by allowing a higher buffer contents. The new assemble lines have been installed and tested and are now in the process of personnel training and fine-tuning. Provisional results of the total redesigning project are: production lead-time reduction from 6 weeks down to less than one week, a reduction of the average stock with at least 50%, considerable increase of volume- and type-flexibility and enlarged productivity.

Future research options are:
Testing the complete product range with the model.
Developing and testing new assignment rules for mechanics to jobs
On line monitoring of production and using simulation for prediction purposes.
Expanding the model with the preceding departments in order to get insight in the intermediate stocks in that area.

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