

proceedings of the
Thirtieth International
MATADOR
Conference



formerly the
International Machine Tool
Design and Research Conference

edited by

A. K. KOCHHAR

PROCEEDINGS OF THE
THIRTIETH INTERNATIONAL
MATADOR
CONFERENCE

held in Manchester
31st March – 1st April 1993

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in association with
MACMILLAN EDUCATION



LOT PRODUCTION: A RULE-BASED EXPERT SYSTEM APPROACH

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The decisions regarding the size and the production release of lots are of fundamental importance in the productive contexts working on lots: the level of client service, the entity of work-in-process and the respect for delivery times depend on these decisions. The authors have developed a model for the realization of a "ruled-based" expert system prototype, which is able to construct and release, at the appropriate moment, lots of satisfactory dimension in respect to specified constraints. In fact, the expert system approach, particularly aimed at implementing the knowledge base of the system, requires first of all the drawing up of a functional model that represents the probable typical logical processes of the decisions to be taken by a human expert. The proposed model carries out an interesting integration of the typical procedures of the Material Requirements Planning (MRP), Capacity Requirements Planning (CRP) and detail scheduling.

1. INTRODUCTION

Though expert system technology is still passing through their initial phase, its potentialities are already evident, essentially due to a totally new approach to traditional software based on algorithmic procedures. A field which has a great interest in these systems is that of business management and in particular production management, an area in which both academic and industrial interests converge. On the theme of the application of expert systems (ES) in production, the authors propose a decisional model for production order release in made-to-order (MTO) firms that work in lots. This model furnished the conceptual and structural elements for the implementation of an expert system prototype, in the Lisp language, constructed by the authors using the ("shell") GoldWorksII tool, and still at the experimental stage. The model utilizes heuristic rules to govern priorities, to coordinate centres for the aggregation of orders and to contain the working capital. It can be applied to various productive concerns which need to work in lots and respect due dates assured to customers.

The authors propose to:

- sum up the logic of order release in the production of lots in MTO firms;
- indicate the possible advantages of the expert system in respect to traditional software;
- describe the characteristics and general functions of an expert system which uses suitable decisional models to release orders in MTO firms;
- present experimental productive context and the decisional model proposed, translated into IF THEN rules, and the dynamic scheduling mechanism;
- supply information useful for the application of the model, on the bases of the initial results obtained.

2. ORDER RELEASE IN LOT PRODUCTION

Production on customer order seems to be becoming more and more widespread, particularly in the case of durable or semi-durable goods [1]. The object of customer service in MTO firms, in terms of respecting due dates and permitting small order quantity, places constraints on the production function, traditionally oriented towards economic efficiency [2]. A "trade-off" exists between the level of service and production efficiency: the availability of a variety of products in the storehouses (to permit a timely and correct filling of the orders) and low production costs (as a result of a large size of the production lot) are in themselves conflicting objectives, the value of the storehouses being equal.

• Delivery times to customers are greater than the sum of the manufacturing and assembly times, thus it is permitted to create a "job-pool" [3], from which it is possible to choose the order of release on the bases of urgency of delivery and according to the work load of the centres. The introduction of this "job-pool" has three great advantages:

1. restriction of "work-in-process" (WIP) - it has been shown that, once a certain quantity of WIP has been reached, the productivity rate does not further increase, while the throughput time continues to increase [4];
2. a greater efficiency of management and control of the remaining jobs, in particular of the progress of the orders and their urgency;
3. the possibility of creating appropriate lots.

On the other hand it has been shown that the presence of a "portfolio" of the correct dimension does not penalize the customer in respect to response time [5]. The time passed in the "order portfolio" is compensated for by the lesser times accumulated by the orders in the queues at each work centre.

- The criteria for aggregation are formulated in order to compact the orders of several customers (in regard to the first phase of production) or several working orders (in regard to successive stages in production) so as to obtain the economic dimension predefined for each phase of production. Usually the aggregation is in conflict with the delivery date. The criteria for aggregations are multiple and different in the various work centres. In the actual course of work the aggregations are mainly in the initial stages, that is in the previously defined "job-pool" represented by the "order portfolio", and in the final stage when one tries to reconstruct the customers order.

Once the orders have been aggregated, the problem becomes the decision on which priority to use to release production. The rules of priority constitute the main points in the activity of "dispatching". The critical element to control is the queue at each work centre. The queue is purely a dynamic phenomenon and must be kept stable for two reasons: 1) to guarantee an adequate backlog for each work centre; 2) to avoid an excessive waiting period.

The rules of priority presuppose a "push logic" in release, in so much as they do not consider the requirements of the work centres farther down the line but rather parameters such as the prevision of requests, saturation of the machines, the containment of "set-ups", etc. [6]. Iskander and Panwalkar [7] have specified about 113 different rules. Browne and Davies [5] using a "job shop" simulation model defined by Brennan et al. [8] tested the use of the most widely used priority rules in order to analyse the impact on throughput time and on respect for delivery times.

3. ORDER RELEASE DECISIONS: ADVANTAGES OF AN EXPERT SYSTEM APPROACH

The ES approach adapts well to production programming activities; in fact these require "expertise" [9] [10]:

- the objectives to be followed are themselves conflicting (in respect to delivery time, saturation of the machines, containment of WIP);
- the restrictions to be respected can be "hard" or "soft", where soft means that the restrictions can be relaxed in a second round; in addition unforeseen events may occur;
- the space of the solution is multidimensional (in the different work centres it is generally advisable to adopt different release criteria and thus the consequences on the production line are different).

The application of IA techniques to the solving of problems connected with order release has undoubtable advantages:

- treatment and evaluation of an enormous bulk of information and at the same time the possibility of

restricting, by means of heuristic rules, the space of the solution; the ability to evaluate situations becomes thus the key to success:

- firing of rules is possible depending on the continually changing state of the knowledge base which represents the shop floor status;
- conflicts or competing requests are treated by the pertinent rules removing constraints and avoiding a halt to the programme;
- realization of simulations with a pruning [11] of the decision trees, thanks to other heuristic rules;
- separation between the descriptive parts of the productive system situation (centres, buffers between centres, centre backlogs) and the procedural parts, with the facility of modifying the rules which make up the procedure of operations;
- construction of new knowledge on the state of the productive system, thanks to the general rules applicable to contingent situations;
- unexpected situation managed by rules summonsed up by the event in hand.

4. CHARACTERISTICS OF A RULE-BASED EXPERT SYSTEM FOR ORDER RELEASE

A "rule-based" ES, which is the most wide spread paradigm [11] [12] is a software product with (fig.1):

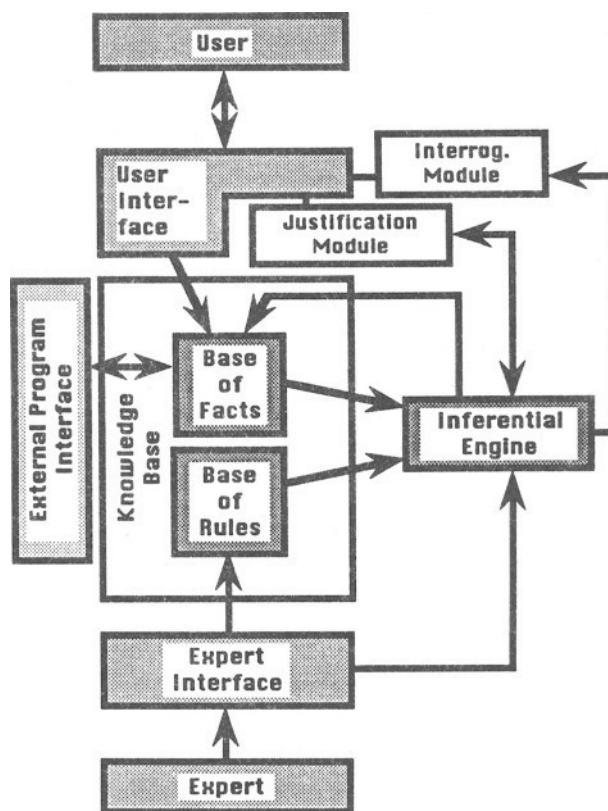


fig.1

- a "knowledge base", consisting of a "base of facts" of a descriptive nature and a "base of rules" (of the IF THEN type) of a procedural nature;
- an "inferential engine", adapted for reasoning according to the strategy "forward", "backward" or "mixed".

The adoption of this strategy is developed through "pattern matching" between parts and sub-parts of rules and the state of "base of facts". The mechanisms of "pattern matching" are governed by the inferential engine.

In short the rules are the following:

IF

*the lower centre is waiting
the upper centre is free
the material for the upper centre is available*

THEN

*fit out the upper centre for the
process required by the lower centre
withdraw the material to be processed
carry out the work*

A forward strategy verifies whether the assertions of the IF part of the rule are present in the base of facts. If this check is positive the base of facts is enriched with the assertions contained in the IF part. These checks are the so-called "pattern matching" by the inferential engine.

It is fundamental to point out the non-deterministic nature of an ES, in other words the capacity to work with new rules based on the results from former rules: in fact the latter have produced new facts, not known beforehand, which have permitted new firings. Thus with these "chaining reasoning" can proceed.

The ES have found and are still finding various applications in production, from process control [13] to diagnosis [14], and industrial automation [15]. Kusiak [16] gives a general picture of IA application to manufacturing (this work should be read for further information). Rodammer and White [17] mention ES for scheduling. There are not many references in the literature concerning the theoretical formulation, the planning and realization of ES in the ambit of order release decisions. Onur and Fabrycky [18] uphold the importance of controlling the input/output dynamics of each work centre; Bechte [19] points out the need for an "order portfolio" of the final customers; Melnyk and Ragatz [20] formulate specifics concerning order release, in particular they state the need for a control of the "order portfolio"; Hendry and Kingsman [3] propose a DSS to manage "lead-times" in MTO firms, and re-elaborate the contribution of Tatsiopoulou et al. [21] forecasting an interface between commercial functions and production. The ES are different from Decision Support Systems (DSS) as they do not only aim at assisting man but even at taking his place ("to replicate expertise").

The main characteristic of an ES for order release in a MTO firm is that it must be able to interpret productive reality under the form of "discrete event" activity [22] [23]: the status of orders, manufacturing apparatus, queues and storehouses are aperiodically modified due to events such as the completion of an order, the release of another order, notification of delay in some orders, an excessive queue for a work centre, a change in machine set-up. The temporization of single events, in addition to reflecting the functioning of a productive system, allows simulations to be realized. During the interval between one event and the next a reconsideration and re-evaluation of already released but not executed orders can be made. Likewise others rules are introduced which must intervene if a solution is not found (and thus it is necessary to relax some constraints) or if there are a number of acceptable solutions (for which a classification is styled considering the importance of the aims and constraints).

The aims can reflect two conflicting needs typical of order release management:

- obtain a high rate of productive efficiency;
- contain the throughput time.

These aims can be transformed into rules that:

- specify the maximum and minimum levels of storage of intermediary storehouses;
- impose a maximum number of machine set-ups in the defined time;
- maintain queues at an acceptable limit but at the same time guarantee sufficient material for running each work centre (no centre must be "starved" [24]).

The constraints are of three types:

- completion of all the orders within the due date remembering that the time for the completion of each lot is a function of the "mix" of the lots present [25];
- load of each machine with one lot at a time;
- finite capacity of the production centres (the capacity of the plants is predetermined and can cope with only a certain percentage variation).

Finally, a part of the rules introduced must consider the complex problem of order aggregation which becomes important when the optimal lot size, from the point of view of productive efficiency, is much higher than the average size of each single order to be manufactured [26].

5. LOT PRODUCTION AND EXPERT SYSTEM: THE PRODUCTIVE CONTEXT IN THE KNOWLEDGE BASE

The productive context reflects the situations typical of lot production:

- work centres through which pass in sequence optimal sizes of lots to undergo different processing in each centre;

- final assembling centres, these too working in lots.

The different optimal sizes of the lots, depending on the work centres, leads to an asynchronous advancement in the orders being processed. In addition the situation is further complicated by set-up times and unitarian run times (i.e. working time per piece) that are different in each work centre, so, for example, a lot of a given size requires different lengths of time to pass through one or another work centre (either preceding or following).

The experimental productive context consists of 9 work centres arranged along three lines (X, Y and Z) and two final assembling centres; storehouses are placed between the work centres, to cope with the asynchronous flow intrinsic in lot production. In the various work centres, for the sake of simplicity in the model, only one process is carried out among all the possible ones for that centre. Three types of raw material are processed in the successive centres along the three production lines (according to the use factor) and the components are then assembled in the final assembling centre (first the components exiting from lines X and Y are assembled then this sub-set is assembled to the product of line Z).

Each centre is characterised by three working parameters:

- minimum lot entity;
- set-up time (for example for a colour change or to change tool);
- unitarian run time.

Working with a minimum lot of a specific entity means that all the order releases for production must provide for a size of the lot to be processed greater than or equal to that entity, even

if the requirements are less. For example with a minimum lot of 100, with a need for 80, in any case 100 pieces are released, while with a request for 120 pieces 120 are released.

The amount of activity in each work centre, contained in a knowledge-base frame of the ES, is described as follows:

- actual job;
- units in the course of production (100 or 120 as in the example above);
- "push" units produced, or the units produced not to meet the needs (in that case "pull" products) but rather to reach the minimum size (20=100-80 in the first example above);
- total time needed to process the lots;
- time remaining on the completion of lots.

Each centre has a backlog which appears as a group of jobs having different priorities (i.e. a queue of working orders); these jobs correspond to orders already released and so have priority over orders to be released so the decision to release does not modify the scheduling of the jobs which constitute the backlog. The model proposed is complete with the possibility of dispatching urgent orders, thus allowing a dynamic scheduling of all the orders, even those already released.

The backlog of jobs in each centre is described by means of a frame in the following way:

- total number of jobs;
- run time and set-up time needed for the group of jobs;
- "free" units, that is "push" units i.e. those not yet assigned to an order, with a description of the type, quantity and date of availability.

Each intermediary storehouse between the work centres, as for the storehouses for raw materials and

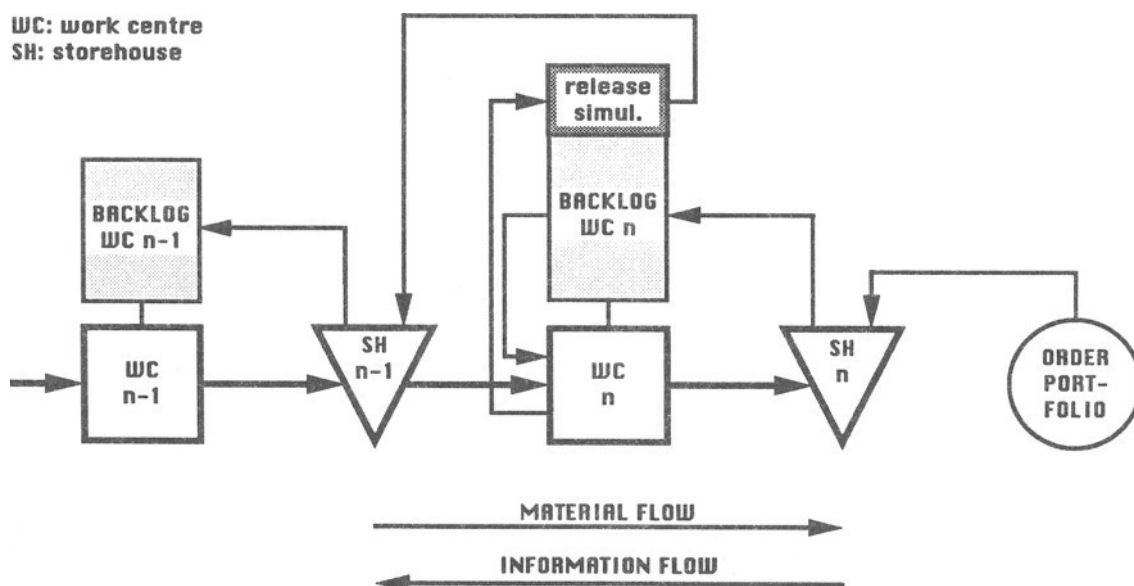


fig.2

finished products, are described by means of a material-code and the amount present respectively of:

- units already assigned to specific orders;
- "free" units.

6. THE EXPERT SYSTEM DECISIONAL MODEL FOR ORDER RELEASE

First we will suppose the productive context to be made up of a single productive line consisting of several work centres in sequence and without re-scheduling the orders already released (6.1); then we will examine the case of more than one line but always in the absence of re-scheduling (6.2). In paragraph 6.3 we will also consider the problem of re-scheduling orders already released.

6.1 Production line consisting of centres working on lots

Loading work centres

The process which, in the simulation mode, leads to the calculation of "slack time" is as follows. First of all a loading is simulated of the centres as a consequence of the release of a certain order (fig.2):

- each order in the "portfolio" induces a search in the storehouse for finished products (SH_N), and successively among the "free" units in the backlog (queues of working orders) of the immediately preceding centre (WC_N), with the aim of filling the order;

- if after this search there is still a definite need, a release in the said centre (WC_N) is simulated as "p+1" times of "p" already in the queue;
- this release must take place according to the "minimum lot" logic and the work time of the centre must be calculated given the unitarian time for the lot entity (greater than or equal to the minimum lot) plus the time for machine setting up, if needed;
- the simulation of release in this work centre

(WC_N) leads to a search for material to process in the upstream storehouse (SH_N-1) and among the "free" units in the backlog of the centre immediately preceding it (SH_N-1);

- this logic moves backwards along the productive system, as far as the raw material storehouses, obtaining a simulated allocation of the materials and a simulated loading of the work centres in preparation for the release of the order.

In fig.3 the backlog of a work centre is represented by an area proportional to the sum of the work hours required by the orders in process queuing at that centre: each centre is represented by its work load derived from the customer orders already released (becoming working orders in each centre) plus the load due to the customer order whose release had been simulated: the latter load is placed high as it is hypothesized that the work-load stack empties from the lower part.

Scheduling the orders

Once loading has been simulated following the release of an order, it is necessary to calculate the "slack time", and this is done by scheduling that order, or defining the starting and finishing date of the processing of the order in all the work centres of the production line. As the start of order processing in a work centre is dependent on the completion of semi-processed pieces released for that order from the work centre immediately above in the line, it appears that the only admissible situation is that of "rising steps" of loads downstream the productive system.

Problems arise when work does not take this ideal form, that is when the centres down the line do not receive the materials to be processed in time (fig.4): if X is the work load (in a unit of time) in centre N, when time X passes without further releases taking place, centre N has processed Y' of the semi-processed pieces of centre N-1 ($Y'=X$), it

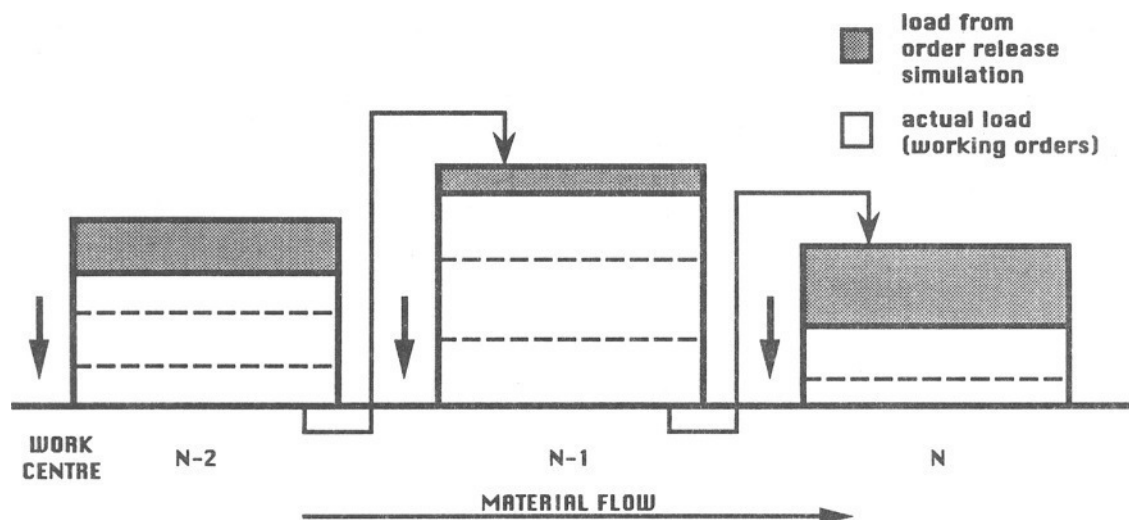


fig.3

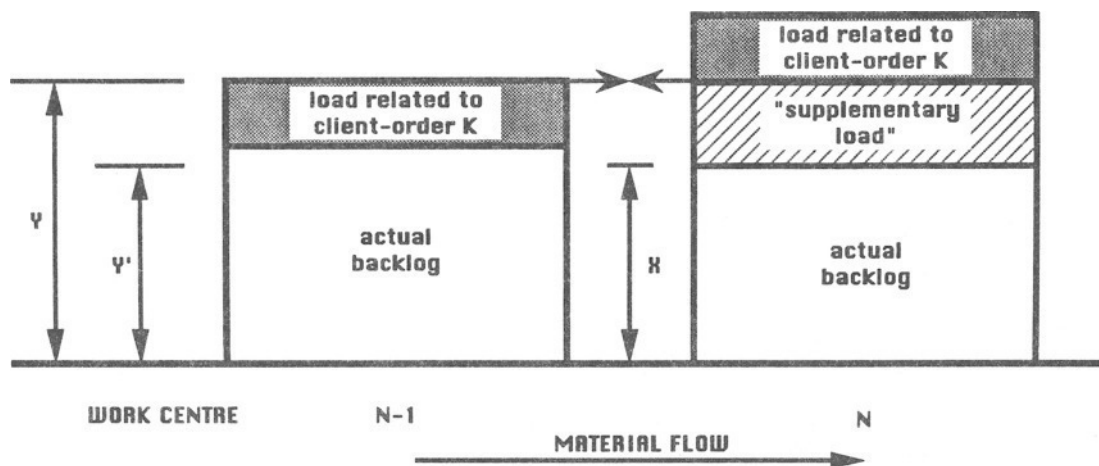


fig.4

is left without work and must wait for the deposit of the lots still being processed or queuing in the centre N-1 ($Y-Y'$ time units). Thus it is necessary to arrange that the job related to the order being tested (shaded in fig.4) starts, in each centre, at a date successive to its completion in the immediately preceding centre. The solution is to "raise" the work load in the lower centres so as to create a "rising steps" profile for the orders being processed, referring to the same customer order in successive centres.

The supplementary loads (one is shown in hatch in fig.4) needed to create the above mentioned profile are not the consequence of needs derived from the order and so must be carefully managed. They must be greater than or equal to the minimum lot, so the termination of work on an order in one centre does not necessarily coincide with the start of work on that order in the successive centre (this can take place even later on if the supplementary load needed to create the step is lower than the minimum lot).

Calculation of "slack time" and the decision to release orders

For a production line whose centres work in lots the calculation of the "slack time" of an order is the difference between the number of days before the due date and the days of work in the downstream centre of the line (for the "rising step" configuration mentioned). If this value is negative it means that it is impossible to complete the order in time and it constitutes a measure of delay. The orders with the lowest "slack" have priority for release. However it may not be the order with the lowest "slack" that is first released, as other factors also influence this decision, and these are taken into account by a series of rules.

These threshold values are deduced from experience and are easily modified in the ES.; they represent the requirements for productive efficiency to such an extent that they prefer the release of

another order even if it is not the one with the minimum "slack".

6.2 Production lines with centres working on lots and final assembling centres

When several lines converge on one or more final assembling centres, the situation becomes complicated. The "slack time" is calculated as the difference between the number of days until the due date and the days of the work load of the centre between those at the end of every line (called $X(M)$, $Y(N)$, $Z(P)$, if X , Y , Z are lines with respectively M , N , P work centres) with the highest work load. Thus there are two alternatives:

- 1) "earliest" loading the work centres of the faster lines;
- 2) "latest" loading the work centres of the faster lines.

In the first case (for example, hypothesizing the existence of a single assembling centre, lots all equal in size and needing 4 hours of processing, $Y(N)$ having the highest load i.e. line Y being the slowest one, with 5 lots scheduled in front of 3 lots for $X(M)$ and $Z(P)$), the lines X and Z make the components of the order released, deposit them into the storehouses and must await line Y for a period of 8 hours (2 lots at 2 hours/lot). To avoid excessive delays, the release of the order could be delayed if the final storehouses have a value, defined as the quantity per unit value by the waiting time, higher than a value considered acceptable. In the second case, all the components are deposited at the same instant, but clearly the centres of the faster lines (for instance, $X(M)$ and $Z(P)$) will first need a "supplementary load", similar to that used in the "rising steps" configuration: for this "supplementary load" a maximum value can be fixed and above which that order cannot be released.

6.3 Dynamic re-scheduling mechanism

Managing an order defined as urgent and thus with processing priority over the others, even if they have already been released, poses the problem

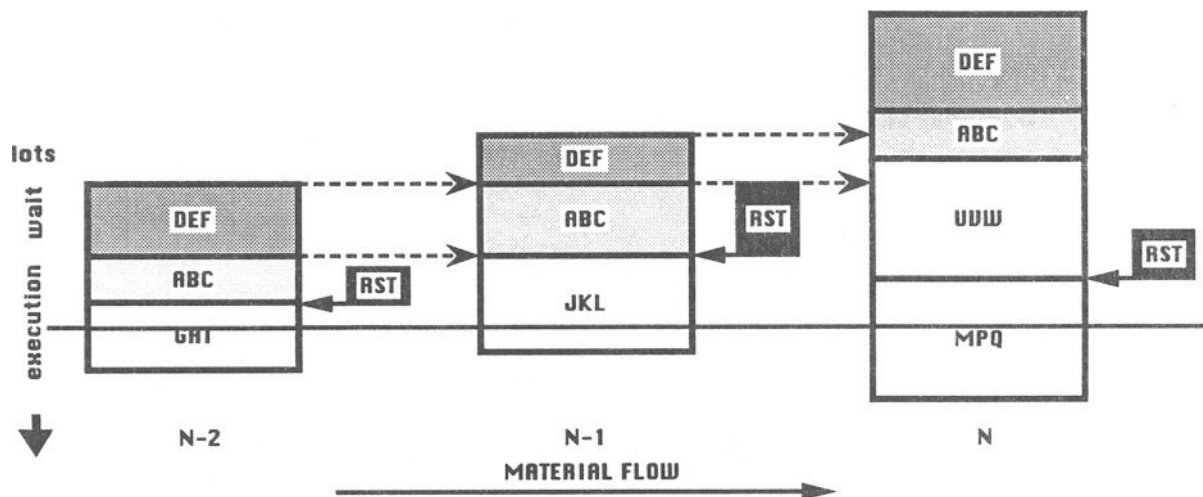


fig.5

of modifying all the previous scheduling regarding the orders released and so the times for filling these same orders. Since the urgent order (called "RST") must be processed at once, it is inserted into the graph representing the work load of the centres, immediately above the lots at present being processed, which are one per centre (these lots are called "GHI", "JKL", "MPQ" in fig.5).

Doing this could alter the "rising steps" progress of each order: in fig.6 a situation is reported where it is necessary to intervene, making use of a "supplementary load", as, after the insertion of the RST order (with the consequent modification in the situation illustrated in fig.5 where progress was satisfactory), the work centre N finds that it must start on RST, the corresponding lot, always referring to the order RST, has not yet been completed in the N-1 work centre). It can be seen in

the same fig.6 how scheduling of the lots relative to the other orders (for example ABC) proceeds well as the depositing data, for each order in a work centre, are identical or successive to the start of processing -of the same order- in the following work centre, even after the insertion of RST order. In this way, in spite of the complexity of managing lots of different sizes (temporals) one has a dynamic re-scheduling which ensures the correct procedure of the WIP.

Three levels of priority are permitted (but even more could be provided for), and for each of these there is a fixed aggregate amount of maximum "supplementary loads" until the priority takes effect; the greater the "supplementary load" allowed the higher the priority. "Supplementary loads" that are too heavy imply the processing of material which do not meet actual requirements ("push logic") so it is

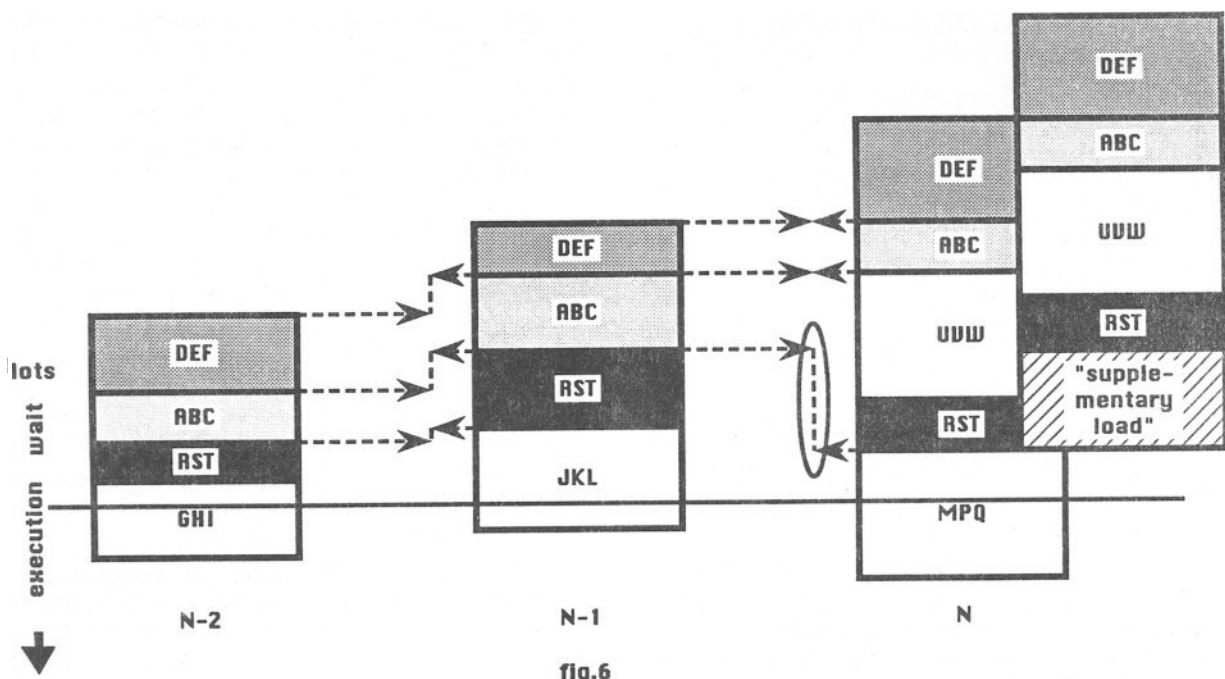


fig.6

preferable to keep the amount as low as possible. If the priority is not accepted by the above mentioned rule, another rule tests the possibility of release not immediately after the lot which is at present being processed, but in any case before lots relative to other orders already released.

7. APPLICATION OF THE MODEL

The modelling proposed has been translated into frames, lists and rules of the IF_THEN_ type and forms the knowledge base of an ES constructed by the "shell". The work centres status, backlogs and the functional parameters of the productive context examined are described by frames; the status of the storehouses and the "order portfolio" are instead in lists. The reasoning logic is described with about 200 rules. The only interfaces foreseen, for the moment, are with file-codes and file-cycles.

The model, whose implementation is permitted by the ES technology based on rules, presents a new way of solving the problems of lot production. In particular, while the MRP (Material Requirements Planning) system calculates the material requirements independently from the availability of capacity tested by the CRP (Capacity Requirements Planning) system, and with further modifications made by the detail scheduling of the SFC (Shop Floor Control), the proposed model could be an interesting alternative, which considers at the same time the material requirements, the capacity and the scheduling of lots, by means of estimating the queuing times and considering the operational constraints in the search for solutions. It is exactly the presence of queues as a dynamic fact - a consequence of the production of lots of different sizes depending on the work centres - and the management of priorities, which cause the crises of MRP traditional algorithms and the need for an "expert" approach.

The ES prototype which implements the proposed model is at present being tested. Its advantages include simplicity of drafting of rules and their insertion into the knowledge base, without having to be placed in a precise point in the list. The first results furnished by the prototype are in accordance with the expectations for which it was designed. It must be added that most of the potential of the proposed solutions are linked to the evolution of supporting tools.

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