The Nottingham Trent University
Faculty of Engineering and Computing
Department of Manufacturing Engineering



# Evaluation of Drum-Buffer-Rope and the 'DISASTER' scheduling package

by

Asier Agirregomezkorta

A thesis submitted in partial fulfilment of the requirements of The Nottingham Trent University for the degree of Master of Philosophy

November 1994

**ABSTRACT**

A growing interest in the detailed scheduling of the shop floor activities has been identified in the last few years. Production scheduling is now often proposed as a vehicle to reduce production lead times and overall inventories, and improve customer service.

The aim of this thesis is to evaluate one such approach to scheduling: the Drum-Buffer-Rope (DBR) scheduling technique and its implementation in the DISASTER scheduling package.

Initially, literature surveys were carried out to define the range of different manufacturing environments, identify the types of solutions to the scheduling problem, and explore the Theory of Constraints (TOC) philosophy which forms the basis of DBR and DISASTER. After this, DBR and DISASTER were evaluated using simulation studies combined with simulation work that had already been published, general use of DISASTER, and visits to companies using DBR and DISASTER.

The main conclusions of the thesis are: firstly, the Drum, Buffer and Rope concepts are not particularly new ideas but rather a new way of combining established ideas together. Secondly, DBR provides a good solution where there is one clearly defined Capacity Constraint Resource (CCR), however, is less effective where there is no single clearly defined CCR and methods such us Linear Programming may produce better results in these circumstances. Even so, the Drum-Buffer-Rope scheduling technique generally performs better than dispatching rules.

The DISASTER scheduling package may not accomplish all that is claimed for it. For example, it has limited modelling capabilities. However, it fully implements the DBR concepts and has additional features to deal with multiple CCRs. Furthermore, because it is an interactive Decision Support System it is useful for strategic planning and because of insights the users can gain using the package, it encourages them to be involved in a Process of on Going Improvement (POOGI).

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ACKNOWLEDGEMENTS

I would like to thank my supervisors Dr. Graham Tranfield and Mr. Roy Stratton for their advice, constant support, and guidance throughout the fulfilment of this project.

I would also like to express my gratitude to:

Rosa, Ane, Aitor, Fernando, Xabi, Mikel, Ritxar, Sorkunde, and Inaki who came with me from the Basque Country to extend our knowledge in the manufacturing area.

The people in the office Chris, Neil and Alex who have all become very good friends.

Jim Corlett for his help in the constant search for information in the library.

GOIER development programme of Eskola Politeknikoa -Mondragon- for giving me this opportunity.

And finally, special thanks to my family and friends for their continual support, patience and belief.

# 1 - INTRODUCTION

The importance of detailed shop floor scheduling is being stressed in the last few years with statements like :

- "The selection of the right scheduling approach is the key to success in any plant" (Harrison 1992).

- Scheduling is the tool that "..has the potential to save businesses large amounts of money while, at the same time, meeting customers' demands" (Palframan 1994).

- Obtain ".. high-quality products, reduce your costs, meet your customers' requirements, and get to markets faster" with the application of particular scheduling softwares (Guise and Lischeska 1992).

A recent shop floor scheduling practice survey performed in U.K. by Little and Jarvis (1993) reveals that although few automated scheduling approaches are currently in use, those companies operating with a detailed shop floor scheduling system have achieved remarkable results (e.g. order and operation due dates performance, less panic/rush jobs, reduced components shortages during production, reduced WIP inventory, and production lead times reduction).

This thesis aims to evaluate the DBR (Drum-Buffer-Rope) scheduling technique and its implementation in the DISASTER scheduling package.

This is achieved by:

1- Surveys of relevant literature.

2- Using simulation models of simple production environments.

3- Using the DISASTER scheduling software.

4- Visiting a number of U.K. and Spanish companies.

The first important consideration for anyone who studies the production scheduling area is that there is not just one scheduling problem. There are a wide variety of different shop floor environments containing specific manufacturing processes, production and product structures, dynamic elements (production disturbances), and final objectives that make detailed shop floor scheduling a complex subject. Chapter 2 therefore discusses the range of different manufacturing environments that are to be covered.

The production management philosophies also determine the role and importance of detailed production scheduling. Chapter 3 discusses the influence the basic philosophies such as MRP/MRP-II, JIT and TOC have on this problem.

There has been considerable theoretical work on a large number of scheduling techniques. These are reviewed in chapter 4 where the main categories of analytical and heuristic techniques are defined.

Chapter 5 includes some general production scheduling statements that generally describe the production scheduling problem.

A significant development in applicable scheduling concepts came with the Theory of Constraints (TOC) production management philosophy, which forms the basis of DBR and DISASTER. Chapter 6 therefore reviews TOC's general problem solving approaches and its production management concepts. While chapter 7 critically compares TOC with other production management methodologies and with MRP/MRP-II and JIT philosophies.

The Drum-Buffer-Rope scheduling technique is evaluated in chapter 8 both on the basis of reported work and on some simulation models. Then, the two most important scheduling softwares applying DBR (OPT and DISASTER) are reviewed in chapters 9 and 10. Chapter 9 analyses OPT based on the published work; while chapter 10 describes DISASTER's structure and scheduling procedure.

Finally, chapter 11 evaluates DISASTER's theoretical base, operational features and schedule feasibility through several models of production environments, some simulation work, previously reviewed subjects (e.g. TOC, OPT, scheduling approaches), and different company visits.

## 2 - THE PRODUCTION SCHEDULING DOMAIN

Detailed production scheduling is included among many other Production Planning and Control activities. Production scheduling function is to allocate the collection of tasks to be done in a certain period of time among the available resources.

However, the scheduling task is complicated by the high variety of manufacturing environments and the individual characteristics exhibited at each of them.

### 2.1 - Production Planning and Control

Production Planning and Control (PPC) is one of the areas of the organization management system. Burbidge (1978) defines "management" as: "the art and science, concerned with *planning, directing* and *controlling* the work of human beings, towards a common aim, in accordance with agreed policies". *Planning* is the process of deciding what to do in the future. *Directing* comprises the operations of issuing orders, instructing those who have to implement the plan, and coordinating and motivating the work of the different people involved in the organization. *Control* compares actual achievements with the plans and feeds back information concerning the performance of the work.

The different management tasks are classified into groups known as "management functions". All the functions are connected with each other, so that they create an integrated organization (decisions taken in one area may affect the normal performance of the tasks at other areas). The functions comprised in the organization management are (see Figure 2.1):

- Finance: includes the tasks concerned with money and profitability analysis of suggested new plans (e.g. investments, cash flow analysis, etc..).
- Personnel: covers company subjects such as wages, welfare and formation.
- Marketing: finds and develops markets, plans the sales, and promotes and distributes the products or services.
- Purchasing: identifies the material suppliers, and deals with buying and delivery of purchases.
- Design: defines the form of product or services.
- Engineering: plans the provision of facilities, their layout and the production routes.

- Quality: defines and controls the product or service quality levels.

- Production Planning and Control: is the management function which plans, directs and controls the material supply and processing activities of a company, so that the specified products are produced by the specified methods to meet an approved sales programme. The PPC activities must be carried out in such a manner that a determined objective function is achieved.

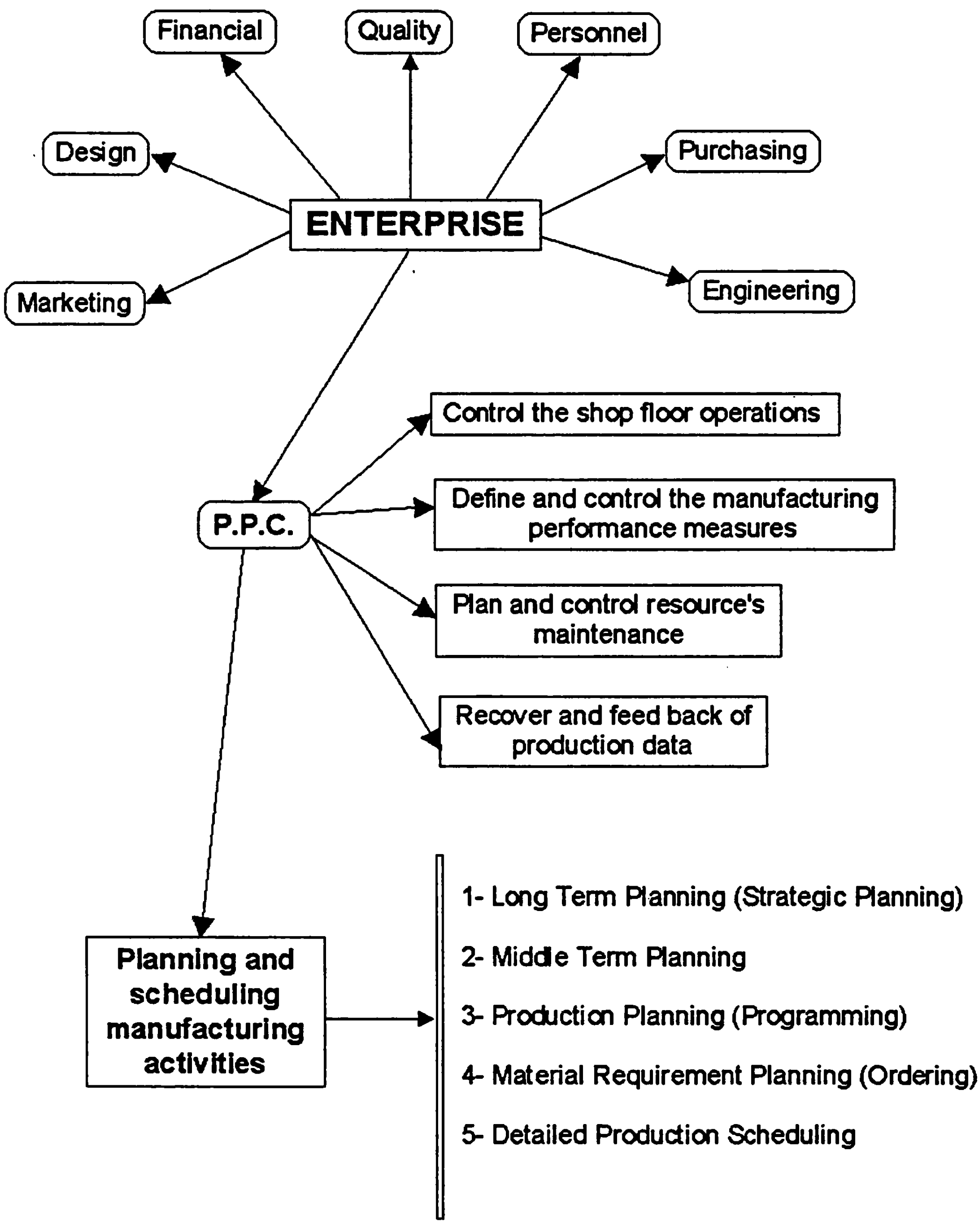



**Figure 2.1**: Management Functions

### 2.1.1 - PPC activities and objectives

The activities PPC is concerned with are:

» Defining the required human and resource capacities to meet the demand.

» Planning and scheduling the manufacturing activities.

» Controlling and planning the required inventory levels.

» Controlling of the shop floor operations.

» Planning and controlling resource maintenance.

» Recovery and feed back of the production data.

» Defining the manufacturing performance measurements and controlling their achievement.

Corke (1987) identifies the following PPC objectives:

» To enable good delivery dates to be offered.

» To get customer orders completed on time.

» To make good use of plant and manpower.

» To avoid excess overall inventory (e.g. raw material, Work in Progress, final products).

» To avoid a succession of production delays and changes which waste the time of operators, production staff, sales staff and management.

» To provide data needed for company planning.

### 2.1.2 - PPC levels

PPC is divided into different levels in order to (a) coordinate all the activities and (b) facilitate the achievement of the established objectives. The tasks at each level are coordinated so that a common aim is pursued.

Many authors have focused their attention on the PPC activities analysis (e.g. Burbidge 1978, 1990; Corke 1987; Hax and Candea 1984; Higgins et. al. 1991; Holstein 1968; Luscombe 1992; Morton and Pentico 1993; and Villa and Watanabe 1993). Despite all the different terminologies used to define each PPC stage, most of the authors coincide in a similar underlying meaning. The levels in which PPC can be divided are:

» Long Term Planning (Strategic Planning): new families of products, jobs and projects are defined at this level. The Strategic Planning includes activities such us: plant location, plant layout, warehouses design, plant and warehouses expansion, etc.. It normally comprises a time horizon of 2 to 5 years.

» Medium Term Planning (1-2 years): the activities at this level are mainly concerned with establishing managerial policies and deciding the necessary resources the organization needs to satisfy the external demand. Production smoothing, production demand forecasts per family of products, and logistic studies are also undertaken at this level.

» Master Production Schedule (Programming): establishes the production output of final products and capacity analysis for a medium/short period of time (normally of one/two months). The amount and determination of the final products could be done based on customer orders or on demand forecasting. Typical decisions taken at this level are: to decide the allocation of overtime at certain resources, to employ alternative machines to process the products, and to decide whether to subcontract some operations or not.

» Material Requirement Planning (Ordering): is concerned with generating the requirements and due dates of manufactured and bought items to meet the Master Production Schedule. Short term resource capacity is analyzed in detail in order to achieve a smooth production flow and avoid temporary resource overloads (production "waves") that would increase inventory and lead time. The time horizon contemplated at this level is normally of 1-2 weeks.

» Detailed Shop Floor Scheduling (1-5 days): establishes the day-to-day scheduling decisions.

### 2.1.3 - Detailed Production Scheduling

Detailed shop floor scheduling can be defined as (Baker, 1974): "the allocation of resources over time to perform a collection of tasks". The schedule generation involves: (1) controlling the release of purchased items to the shop floor, (2) designating the resources needed to execute each operation in the routing, (3) determining the batch size for each job, (4) sequencing the operations which will result in the completion of a job, and (5) assigning the times at which each operation in the routing will start and finish execution.

Problems arise when a common set of resources must be shared to make a variety of different products during the same period of time. The objective of production scheduling is then to find an efficient and effective way to assign and sequence the use of this shared resources. However, the following factors influence the schedule generation: production due-dates, cost restrictions, material release dates, job priorities, lot size restrictions, resources capacities, operation precedences, labour requirements, and business policies. Further, the dynamic and stochastic nature of production environments introduce more complicating elements to take into account in the detailed shop floor scheduling process.

### 2.2 - Types of manufacturing systems

A "Manufacturing system" is an organized activity that employs a series of value-adding production processes to transform the raw materials and components into finished saleable products. A broader consideration of a manufacturing systems is shown in Figure 2.2.

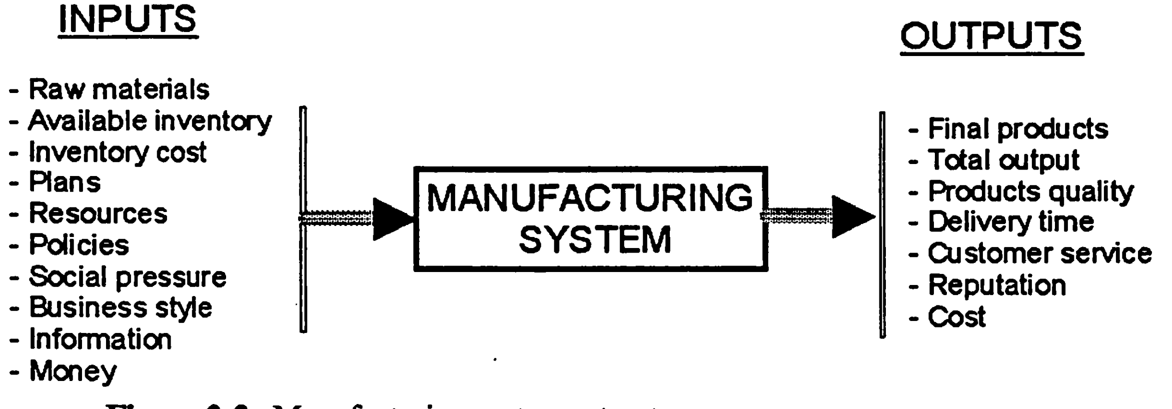



**Figure 2.2**: Manufacturing systems structure

The manufacturing system must have the organizational infrastructure that adequately answers the targeted market. This organizational structure will contain aspects like: process technology, product/service type, demand volume, order winning criteria, product change degree, plant layout, process and labour flexibility, etc.. that determine the behaviour of the whole system. Production management -with shop floor control and scheduling as part of the PPC-, must correlate with the characteristics of the manufacturing environment, and adequately address the inherent production problems. The traditional way in which production environments have been classified is reviewed in the next section.

### 2.2.1 - Traditional classification of manufacturing systems

The traditional or "classic" way of classifying the manufacturing systems is dividing them into five main groups (Hill 1985): project, jobbing, batch, line, and continuous process.

*** Project**

Companies which produce large scale, one-off, complex products will normally provide these on a project basis. The project type production system concerns the provision of a unique product or service requiring large scale of inputs to be coordinated so as to achieve a customer requirement. Product examples include civil engineering contracts and aerospace programmes; while service examples include strategy-based consultancy assignments.

Often, the necessary resource inputs are taken to the point where the product is to be produced or the service provided. The reason for this is simply that it is not practical to move the product once it has been built or to establish the service anywhere but where it is to be implemented and used.

All the activities, including support functions, will normally be controlled in the form of a total system for the duration of the project and under the direction of a coordination team. Similarly, resources will be allocated for the duration of the project and these, like the supporting functions, will be reallocated once their part of the task is completed or at the end of the project.

The selection of project as the appropriate process is based upon two features. Firstly, the product is a one-off, customer specified requirement (*engineer-to-order*) and, secondly, it is often too large to be moved or simply cannot be moved once completed.

Operations manager problem is one of coordinating a large number of interrelated activities and resources in such a way as to achieve the customer requirements whilst minimizing costs through the process. These activities are normally performed in a three steps procedure:

a) Plan. Establishes all the activities and the time they take to be completed

b) Schedule. Sequences the activities by contemplating aspects like cost and the availability of people, processes and materials.

c) Control. Feeds back information about the work performance so that the schedule can be modified when major deviations occur.

*** Jobbing (job-shop, unit or one-off)**

Organizations which choose jobbing type of manufacturing system will once again be providing products or services of an individual nature and made to customer specification. The difference between jobbing and project, is that in jobbing the resources remain on the same site and the products/services flow through them.

As it is a one-off provision, this means that the product will not be required again in its exact form or, if it is, the demand will tend to be irregular with long time periods between one order and the next. For this reason, investment in the manufacturing process (e.g. in jigs, fixtures and specialist plant) will not normally be warranted.

Product examples include a purpose-built piece of equipment, hand made, built-in furniture to meet specified customer requirements, a customer designed and specified control unit, hand-made shoes or clothing, and purpose-built tooling. Service examples include a tailor-made management development programme, the design and installation of a computer system, and a banquet at a restaurant own premises.

The one-off product involved requires that the supplier interprets the customer's design and specification whilst applying relatively high level of skills in the conversion process. This interpretation will be in the hands of skilled employees whose experience in this type of work will be essential. Once the design is specified, one or possibly a small number of skilled workers will be responsible for deciding the best way to complete the task on hand and for carrying out the work. It includes a level of responsibility over scheduling, and some involvement with the arrangements for outside subcontracted phases.

The control at a jobbing manufacturing system loads only jobs for which an order has been received. It then needs to ensure that the job goes through the required sequence of operations and that the agreed delivery date is met. Furthermore, due to the uncertain duration of the jobs' completion, there is a need to include this uncertainty in the control and scheduling procedures.

*** Batch (intermittent)**

This form of process will be chosen when the product/service volumes have increased and sales of these items are repeated. This means that the business can justify investment in capturing data, in deciding how best to complete the tasks, and in the processes necessary to make the product or provide the service.

The production procedure followed in the intermittent environment is to divide the manufacturing task into a series of operations which together will complete the final product. The reason is simply to determine the most effective manufacturing route so that low cost products are produced. At this stage, suitable jigs and fixtures will be identified in order to help reduce the processing times. This investment is justified by the total product throughput over time.

Once the job is divided into a series of operations, the whole order is processed at the first process step of the route. Then, the items are transported to the next operation, processed, moved to the succeeding one, and so on, until the final product is obtained.

The essential characteristic of batch is that to produce another product or provide another service, the process has to be stopped and reset. Manufacturing examples include component manufacture and fabrication (e.g. car components, domestic products for the kitchen and bathroom, and items for the office), and moulding processes. Service examples include computer bureau that processes the work of several clients on the same piece of hardware.

The control task at the intermittent manufacturing systems involves monitoring jobs trough the process and assessing the impact of the volume and product/service mix changes over time against specific process capacities.

On the other hand, a typical scheduling procedure used is to break down each order into the sequence of operations and then, having assessed the time required to do each operation, load each job into the process. At the same time, it will be ensured that the total loading for each process does not exceed the available capacity.

In order to cope with the large amount of information involved, a microcomputer will often be the way to handle not only the production/operations scheduling and control, but also the inventory control.

The characteristics of batch manufacturing processes are between those of jobbing and production line. Sometimes, if the product/service volume is low, batch manufacturing system will show similar attributes of those of jobbing. While, if the volume is high, the characteristics will resemble those of line.

*** Line (repetitive, flowline)**

With further increases in volumes, investment is made to provide a process that is dedicated to the needs of a single or normally a small range of products. In line manufacturing systems each product/service will pass trough the same sequence of operations. The essential differences between line and batch are that (a) line normally has a predefined output rate dictated by the automated resources, and (b) that to produce another product or provide another service in line manufacturing system, the process does not have to be stopped and reset.

A repetitive production system is characterized by the production of discrete units in a relatively high speed and volume. Materials tend to move in a continuous flow during production, but different items may be produced sequentially within that flow.

Product examples include domestic appliances and motor vehicles assembly lines. Service examples are not so common, but we can find line processes to complete services in certain preparatory operations in fast food restaurants such as McDonald's.

The control problems identified in line manufacturing systems are concerned with keeping a line fed with the components and sub-assemblies required to meet the programme. A final assembly schedule is normally created, with component and sub-assembly programs that will ensure that the line is continually fed.

Authors like Aneke and Carrie (1984), De Toni and Panizzolo (1992) and Wild (1971), have focused their attention on classifying the different types of production lines. Some of the different production lines that can be encountered are:

- Single-model lines: used for the production of single version of only one item (there is no need to alter the set-up of the line). Examples of this type of line are: (a) single product single machine system and (b) single product multi-machine system.

- Multi-model lines: two or more similar products are produced in separate batches (normally with the rearrangement of the flowline between batches). Varieties of multi-model lines are: (a) multi-product single machine system, (b) multi-product sequential flowline, (c) multi-product bypass flowline, (d) multi-product bytracking flowline, and (e) multi-product multidirectional backtracking system.

- Mixed-model lines: two or more similar models of many items are produced simultaneously. Examples of mixed-model lines are: (a) mixed product single machine system, (b) mixed product sequential flowline and (c) mixed product bypass flowline.

*** Continuous process (mass)**

Continuous processes are inflexible, dedicated processes used to handle high volumes of small range of products. The process is dedicated to run all day and every day with minimum shutdowns due to the high starting up cost.

Continuous process is characterized for the nature of the materials being processed. The materials -like for example: fluids, gases and food- lend themselves to be moved easily from one part of the process to another.

While in line there were manual inputs into the manufacture of the products as they passed along, in continuous processing the materials will be transferred automatically from one part of the process to the next, monitoring and self-adjusting the flow and quality. The labour task in these situations is predominantly involved in checking the system.

The scheduling task at mass environments is relatively easy. It only requires the determination of the material release, and then the flow goes forward by itself, taking -normally- a few days to process all the products.

The best example of the products manufactured in a continuous process manner are petrochemicals.

*** Hybrid production systems**

Hybrid systems are created to fill the gap between some of the manufacturing systems. They are normally generated from a mix of two different production environments, so that particular products or services needs are properly answered. The different types of hybrid manufacturing systems are (see Figure 2.3):

- <u>Numerical Control (NC) machines</u>: are the processes which automatically performs the required operations according to a detailed set of coded instructions. They are called numerical control because they are based on mathematical information.

Compared with conventional equipment, NC machines offer more accuracy, consistency and flexibility. Design changes and modifications only require to alter the initial instructions. NC machines' installation requires certain level of specialist support and skills for the workforce and supervisors.

- <u>Machining Centres</u>: are the combination of different NC machines in one single location to perform the maximum number of operations. The product will pass trough a sequence of operations (similar to line), with the subsequent reduction in WIP.

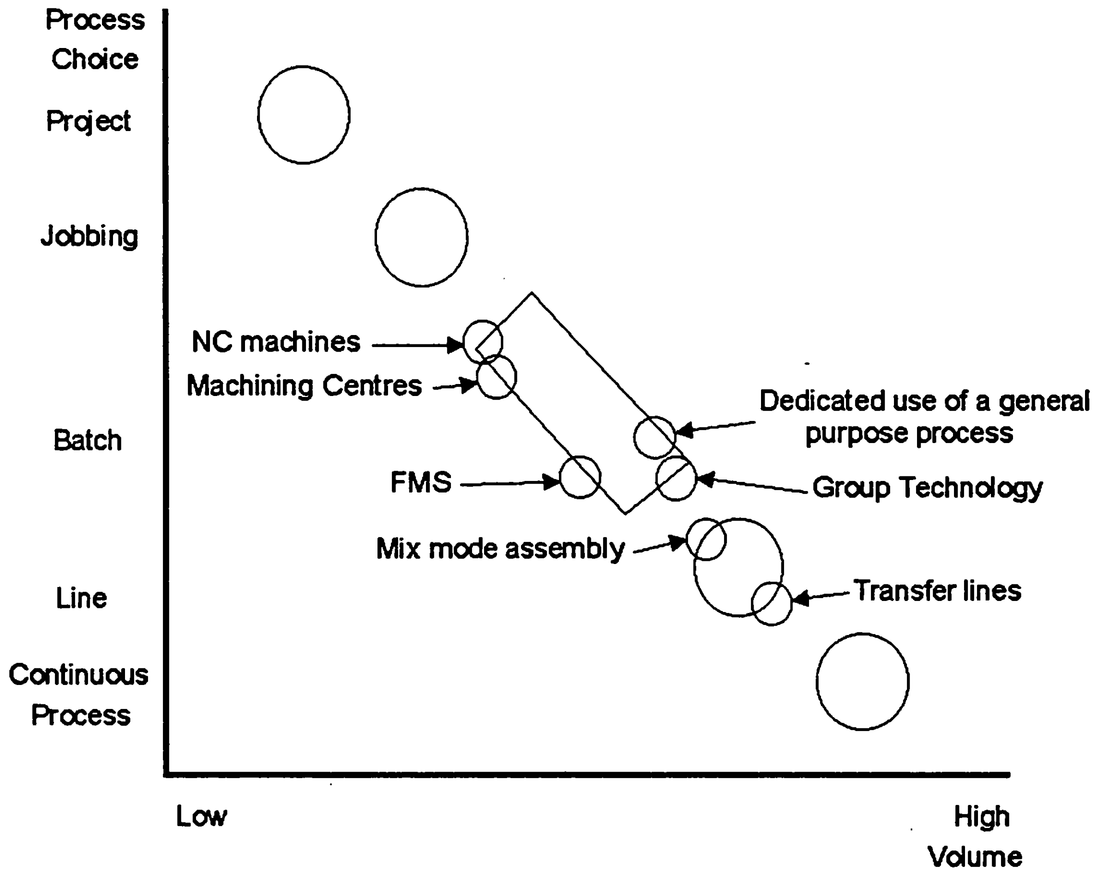



**Figure 2.3**: Types of hybrid production systems (source: Hill -1985-)

- Flexible manufacturing systems (FMS): are a combination of NC machines, automated materials handling and direct numerical control (DNC) for the purpose of extending the benefits of NC to mid-volume manufacturing situations and mid-variety of products. The philosophy of FMS coincide with that of Machining Centres: maximize the combination of operations completed at a single location. FMS are sometimes considered a mini-CIM system, designed to fill the gap between high volume hard automation transfer lines and NC machines.

- Dedicated use of a general purpose process: in this case, due to the high production volume involved, a non-NC equipment is allocated for the sole production of a specific part. The flexibility of a general purpose process is still retained for the case when demand volume decreases and the machine has to be reallocated to produce different products.

- Group Technology (cells): involves the grouping of different machines (normally non-NC) in the same part of the shop-floor to allow the production of a family of products. Reduced lead times and lower work-in-progress inventory are gained with the choice of this process type. On the contrary, process flexibility is not of the same order of FMS and the equipment will have to be returned to the initial location when demand volumes decrease.

- Mix mode assembly lines: are assembly lines which are designed to cope with a range of products in any scheduled combination. This is achieved by the use of computer controlled flow lines which schedule the workloads at the various stations. This kind of processes are designed to cope with high volume batch products by transferring the basis of batch production to line.

- Transfer lines: are considered a hybrid between line and continuous process, and are applied for very high demand volumes. Production volumes justify investment to design a process that automatically moves a part from one station to the next, completes the task and checks the quality of the product.

### 2.2.2 - Overview of the manufacturing systems classifications

There is a huge variety of other manufacturing system's classifications apart from the traditional or "classic" way just reviewed. The different features in which the production environments can be grouped are (Table 2.1 summarizes some of the terms employed and highlights their similitudes):

- Group - 1: based on the production method employed. Authors> a) Hill (1985), b) Wild (1983), and c) Browne et.al. (1988).
- Group - 2: based on the number of times the same item is produced. Authors> a) Wild (1983), b) Granger and Sounders (1990), and c) De Toni and Panizzolo (1992).
- Group - 3: based on the customer order decoupling point. Author> Wortmann (1992).
- Group - 4: based on the plant layout. Authors> a) Burbidge (1971), b) Hill (1987), and c) Wild (1983).
- Group - 5: based on the ratio of material varieties to product varieties. Author> Burbidge (1990).
- Group - 6: based on the dominant resource/product interaction. Authors> a) Umble and Srikanth (1990), and b) Harrison (1991) and Frizelle (1989').

| GROUP 1a | GROUP 1b | GROUP 1c | GROUP 2a | GROUP 2b | GROUP 2c | GROUP 3 | GROUP 4a | GROUP 4b | GROUP 4c | GROUP 5 | GROUP 6a | GROUP 6b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Project | ---------- | Craftsman | Unit | One off | Individual/ Unique | Engineer-to-order | ---------- | Fixed position layout | Fixed position layout | ---------- | ---------- | ---------- |
| Jobbing | Jobbing | Jobbing shop | (Unit) | (One off) | (Individual/ Unique) | Make-to-order (Engineer-to-order) | Functional layout | Process layout | Process layout | ---------- | ---------- | ---------- |
| Batch | Batch/ intermittent | Batch | Intermittent | Discrete | Intermittent/ discontinous | Make-to-stock (Assemble-to-order) | Functional layout (Group layout) | Process layout | Process layout (Group layout) | Square Industry (Explosive Industry) | (A-plant) (T-plant) | (A-plant) (T-plant) |
| Line | Repetitive | ---------- | Repetitive | Repetitive | Repetitive | Make-to-stock (Assemble-to-order) | Line layout | Product/ Flow layout | Product layout | Process Industry (Implosive Industry) | (V-plant) ((T-plant)) | (I-plant) (V-plant) ((T-plant)) |
| Continuous Process | Continuous process/ mass | Continuous process | Mass | Process | Continuous | Make-to-stock | Line layout | Product/ Flow layout | Product layout | Process Industry | ---------- | ---------- |

Table 2.1: Classification of manufacturing systems

# 3 - MANAGEMENT OF PRODUCTION SCHEDULING

The selection of the scheduling software employed to produce the detailed shop floor schedules depends on the characteristics of the production environment as well as on the specific production management approach utilized. This chapter discusses the way the three most important production management philosophies determine the role and importance of production scheduling.

## 3.1 - MRP/MRP-II: "top down" hierarchical approach

Material Requirement Planning (MRP) was created in the early 1960s in the USA and is a centralized computer system that explodes final products requirements into time-phased shortage list for each manufacture and bought component at all the stages of the manufacturing process.

MRP/MRP-II is based on a hierarchical PPC structure (see Figure 3.1) in which most of the effort is focused on the planning level; while at the shop floor level, the responsibility of following the schedules is placed in the shop floor personnel.

+ Planning level

In the Production Planning and MPS stages, the production management policies and the planned final products by quantity and date are defined. As the MPS drives MRP any errors in it would lead to unrealistic schedules or unnecessary products manufacture.

The Rough Cut Capacity Planning (RCCP) is employed at this level to check the capacity on a few key resources and ensure that the MPS is realistic.

+ Scheduling of the planned orders at the MRP level

MRP creates a time-phased requirement for both, purchased and manufactured items, to meet the MPS needs. The lead times employed at this level are fixed, and represent the average lead time the components require to be processed. Manufacturing operations due dates are defined from the final products due dates by scheduling backwards based on the planned lead times and assuming infinite resource capacity.

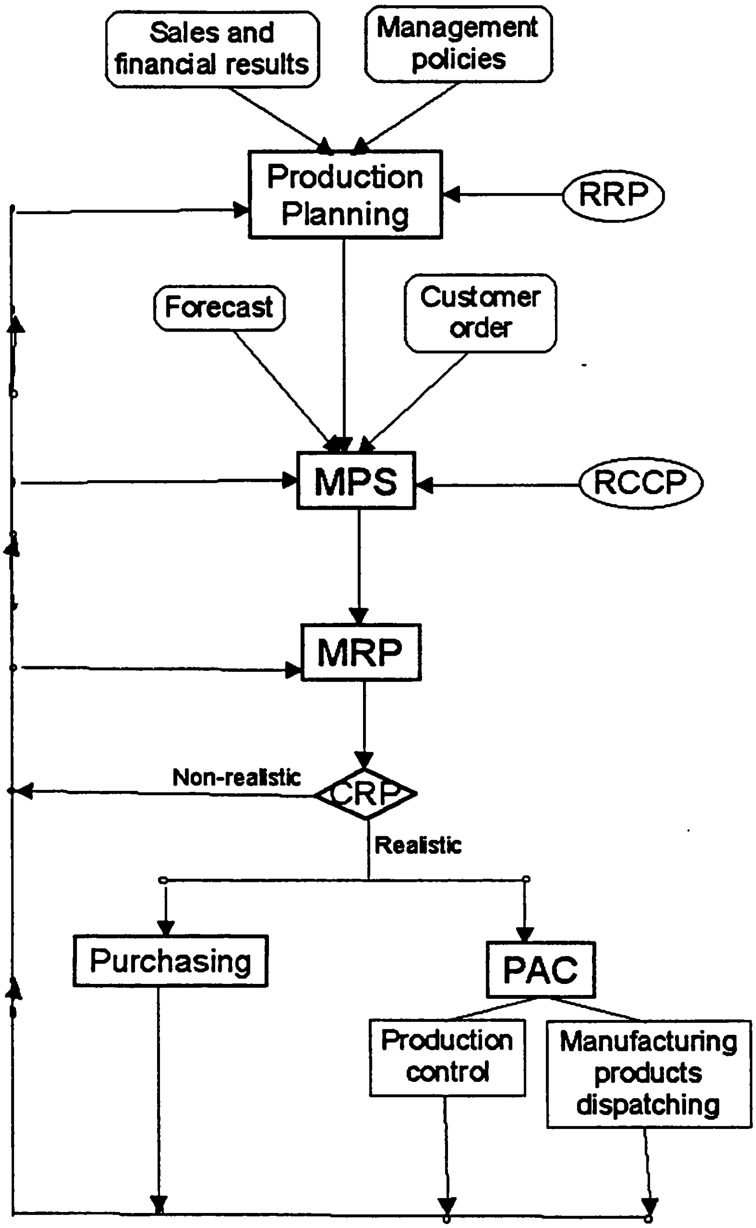



**Figure 3.1**: PPC structure in MRP/MRP-II

Capacity Requirement Planning is performed after each MRP run. CRP produces a detailed profile of the capacity required in each work centre by exploding the manufacturing orders through the product routings.

<u>+ Detailed shop floor scheduling at PAC level</u>

As a result of (a) assuming infinite resource capacity, and (b) inflating the planned lead times (according to Browne et.al -1988- is common that only 5% of the planned lead time is formed by setup and process time, while the rest is transport and queue time) unrealistic detailed shop floor schedules are often created. This fact puts the responsibility of following the schedule and solving the problems onto the shop floor personnel.

+ Production control in MRP/MRP-II

MRP/MRP-II exhibits a centralised control structure in a sense that the system only suggests what must be done to meet the MPS, and then leaves all decisions in the hands of the planner.

Moreover, MRP/MRP-II promotes a production control focused on the production orders (it suggests only the components required to fulfil the MPS) and then applies the "Push" named logic. This shop floor control logic involves the fabrication of the products by focusing initially on the material release dates, and then pushing forward according to the manufacturing dates of the different process stages.

### 3.2 - JIT: holistic approach

Just-in-Time (JIT) management philosophy was created in the Japanese Toyota plant in the 1960s, and seeks the elimination of all the process stages that do not add value to the product (i.e. rework, storage and inspection) by achieving excellence in all phases of the product completion process (design, purchasing, manufacturing and distribution). Preston (1990), defines JIT as "the scheduling philosophy that dictates reduced materials inventories and minimum WIP in order to aid process improvement and reduce process variability".

+ Goals

JIT seeks to design an efficient manufacturing system in which complexity is replaced by simplicity and the following goals are achieved: zero defects (100% good units), zero inventories, zero set-up times, lot size of one, zero lead time, zero handling, and zero breakdowns.

The final objective of JIT management philosophy is to produce the required items, at the required quality and in the required quantities, at the precise time they are required.

+ Overall production management philosophy

JIT must be understood as a combination of three different parts (Browne et.al. 1988):

» JIT philosophical approach to manufacturing: it involves a continuous commitment of the overall organization to pursue the excellence in all phases of manufacturing system design and operation. JIT approach incorporates business perspective by linking market demand, production aspects and suppliers.

» JIT techniques for designing and planning the manufacturing system: JIT seeks to reduce production lead times and achieve a fast and smooth production flow by applying: (a) product design for ease of manufacture and assembly (high product variety with low process variety by using flexible equipment, flexible workforce, and superior production engineering), (b) manufacturing planning techniques (production smoothing techniques), (c) techniques to simplify the manufacturing process (U-shaped product based layout with multiskilled operators and single unit production and transport batches), and (d) total quality control aspects (elimination of all possible sources of defects from the manufacturing process).

» JIT technique for shop floor control: shop floor control and scheduling are carried out by a technique called KANBAN. Many associate JIT with KANBAN, forgetting the great effort employed by the underlying philosophy and techniques to simplify the manufacturing system in order to facilitate production control and scheduling.

+ KANBAN technique

KANBAN is the part of the overall JIT approach that executes the just-in-time product deliveries on the shop floor level. It acts like a PAC, controlling the product flow through the plant, the build up of inventory, determining which products produce next, and encouraging the participation of the multiskilled operators. KANBAN is the Japanese word for "card" and there are many particular Kanban applications (e.g. single card Kanban and double card system). The Kanban technique in the Toyota company works in the following manner (Shingo 1989):

There are two different kind of cards:

- Work-in-Process kanban: serves as identification and job instruction tag.
- Withdrawal kanban: serves as identification and transfer tag.

The flow of the two cards is:

1- When the parts stocked in front of the assembly operation are removed, the withdrawal kanban enclosed in their container is placed on a specific board.

2- The worker responsible of the process previous to assembly: (a) takes the withdrawal kanban, (b) removes the work-in-process kanban from the pallet with the products that are already in the process station, (c) puts this work-in-process Kanban in a specific board, and (d) places the withdrawal kanban on the pallet with the parts to be sent to assembly.

3- The work-in-process kanban removed from the pallet and placed in the board serves as a job instruction tag to prompt the processing of the parts required in assembly.

4- When the parts are again processed in the assembly operation, the withdrawal card is removed, and the parts are pulled from the feeding processes. The procedure starts again and continues down the production process.

Further characteristics of JIT's management of production scheduling are:

- "Real" time scheduling: with Kanban as a dynamic production control system, jobs are not scheduled in advance, but rather production is authorized based on current status information.

- Visual scheduling: there is no need for computerized tools at the daily shop floor level because the Kanban cards display the products that must be processed.

- Autonomous scheduling (local scheduling decisions): the operators of the manufacturing cells decide what, when and how much to produce based on the information obtained from the cards stuck in the boards.

- Finite resource capacity: by scheduling in real time, the finite capacity of the resources is taken into account.

+ Production Control

Just In Time is understood as a holistic approach that enables the separation of the plant into different production subsystems -manufacturing cells-. As a consequence, production control is influenced by the autonomy exhibited by these subsystems. JIT's production control characteristics are:

- Decentralised control: multi-skilled operators and supervisors decide what and when to manufacture the products. This leads to a quite easy to run decentralised system in which quality and maintenance operations are also carried out by the workforce.

- Hierarchical PPC structure: the planning function is divided into several stages that cover different time horizons and seek to facilitate the control task.

- Pull logic (dynamic production control system): JIT's production control is performed by the "PULL" called logic. This technique passes the demand for final products down the chain of production, sequentially through its various stages and processes. In this fashion, inventory levels at the various production processes are pulled along by actual levels of market demand. Moreover, resource finite capacity is taken into account when parts are pulled based on real time assembly requirements.

### 3.3 - TOC: "bottom up" finite scheduling approach

The Theory of Constraints (TOC) production management philosophy is thoroughly analyzed in chapters 6 and 7. However, it can be anticipated that TOC seeks to synchronize the manufacturing operations by identifying and fully exploiting the constraints of the system and then subordinating the rest of the resources to their optimal schedule. TOC tries to efficiently manage the shop floor operations -"bottom up" approach- in order to achieve all manufacturing systems Goal (Goldratt and Cox 1984): "To make more money now as well as in the future".

TOC-based scheduling softwares (OPT and DISASTER) assume resource finite capacity to realistically represent the limitations of the shop floor and obtain feasible schedules in which base production decisions. Finite scheduling will (a) recognize the resources with less relative production capacity, (b) display temporary resource overloads, (c) balance work flows based on capacity constraints, (d) obtain, realistic quotable production due dates, and (e) permit 'What if' simulations for capacity planning analysis.

However, finite capacity approaches remove the responsibility of shop floor personnel for making scheduling decisions based on their experience, and have the additional drawback that for unpredictable process times continual rescheduling would take place.

### 3.4 - General overview

The three approaches to managing production scheduling in real manufacturing systems can be summarized as follows (see Figure 3.2):

- "Top down" approach (MRP/MRP-II): MRP/MRP-II is primarily concerned with creating valid production plans that meet demand (product mix). Most of the effort is thus spent at the planning level, while at the shop floor level operators and foremen are responsible for fulfilling the -often- unrealistic schedules.

- Holistic approach (JIT): JIT seeks to achieve overall manufacturing excellence and simplify the production environment to such an extent that, in the end, the complexity of production control and scheduling is greatly reduced. Moreover, particular attention is given at the planning level to define the production mix that would allow a smooth and fast production flow (production smoothing techniques).

- "Bottom up" approach (TOC): this approach seeks to realistically represent and efficiently manage the manufacturing operations as a basis of the overall decision making. Detailed shop floor scheduling is thus the 'central' activity from which the rest of the production management functions are derived.

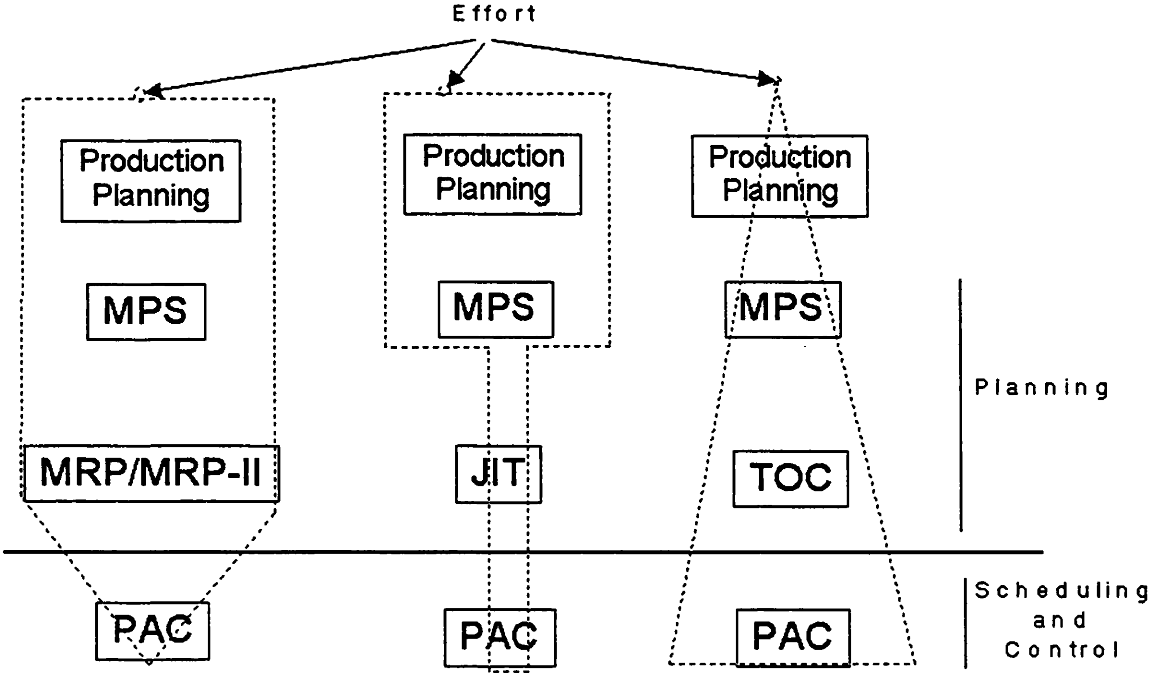



**Figure 3.2**: planning and shop floor scheduling/control effort in the production management approaches

# 4 - PRODUCTION SCHEDULING APPROACHES

## 4.1 - Introduction

The two TOC-based most important scheduling softwares (i.e. DISASTER and OPT) are applied in discrete parts manufacturing environments (e.g. jobbing, batch, and line). In these same environments, there are other scheduling methods and techniques principally included in the main categories of analytical and heuristic approaches that tackle the scheduling problem in different manners. The scope of this chapter is review the theoretical work performed in this area in order to examine the way the different production scheduling approaches address the detailed shop floor scheduling problem.

The scheduling approaches reviewed are:

1- Analytical approaches (Operations Research methodology).

2- Heuristic approaches.

3- Artificial Intelligence (expert systems).

4- Simulation.

## 4.2 - Analytical approaches (Operations Research methodology)

Analytical scheduling approaches grew up strongly in 1970. This methodology is based on Taylor's idea of complete analysis of the factors that influence the rational organization of production systems and that scientifically derived designs performed better than those acquired empirically.

The analytical methodology favours the system-theoretic approach by modelling the scheduling problem as a set of constraints. A given problem is reduced to its formal, mathematical structure by the creation of an algorithm that produces an optimal solution to the stated generic problem. To allow the use of mathematical models, the scheduling problem has to be highly simplified by assuming it static and deterministic (an ideal environment). The following scheduling assumptions are normally made in most of the analytical studies (French 1982; MacCarthy and Liu 1993):

1- Each job is an entity: although the job is composed of various operations, these operations cannot be processed simultaneously.

2- No pre-emption is allowed: each operation once started, must be completed before another operation may be started on the same machine.

3- Machines are always available.

4- Machines never break down.

5- All jobs are ready at time zero.

6- Any job can be processed on at most one machine at any time.

7- Processing times and due dates are known in advance -deterministic approach- and are independent of the schedule.

8- Setup times are independent of the schedules and are included in processing times.

9- No cancellation is allowed: the job must be processed to completion.

10- In-process inventory is allowed.

11- There is only one of each type of machine.

12- Machines may be idle.

13- No machine may process more than one operation at a time.

14- The technological constraints are known in advance and are immutable.

15- There is no randomness.

16- Is not permitted to split the batches.

17- It is assumed that the data is accurate.

18- Transport time of jobs between facilities is neglected.

The different scheduling methodologies contained in the analytical approach (also called Optimization-based scheduling methods) can be divided into two main groups:

1- *Mathematical programming techniques*: French (1982) maintains that "mathematical programming is a family of techniques for optimising a function subject to constraints upon independent variables". In production scheduling the optimization of a defined objective is pursued by taking into account all technological constraints. The following techniques are included in the mathematical programming approach:

- Efficient optimal algorithms: these algorithms, based on the production variables of the problem, generate an optimal solution by following a simple set of rules which determine the exact order of processing. The time taken to find the optimal solution is a polynomial function of the problem variables (jobs and machines).

This method can only be applied to a relatively narrow problem classes (e.g. the single and two machine cases and the possible application to the bottleneck machines scheduling problem). The narrow application area and the enormous computational time needed to reach an optimal solution are the main drawbacks of this approach. Two examples of efficient optimal algorithms are Johnson's algorithm and Moore's algorithm (Graves 1981).

- Linear programming: this technique formulates the objectives and constraints as a set of linear equations, which are then simultaneously solved, and the objective function achieved.

The advantage of linear programming is that once the equations have been set for a particular problem, the periodic schedule generation is simple and rapid. On the other hand, the main drawback is that it is difficult and time consuming to construct, in mathematical form, an accurate model of the scheduling problem (Niland 1970).

There are two main applications of this technique. One is concerned with the assignment of jobs to different machines, each with different capabilities and costs (this situation is typical of many jobbing cases). The second possible application is concerned with process oriented plants. In those sort of plants a different number of choices of how to operate the several processing stages can coexist.

- Integer programming formulations: the only difference with efficient optimal algorithms is that some of the independent variables are constrained to be integral. Often, they are only allowed the values of 0 and 1 and are used to indicate the absence or presence of some property. As a result, scheduling problems can be solved more easily.

2- *Enumerative optimal methods:* mathematical programming approaches exist only for a small class of scheduling problems. However, more complex problems are said to be **NP-hard or NP-complete** (Non-polynomial). This means that the number of possible solutions increases exponentially with the size of the scheduling problem. It has been demonstrated that for a simple "n" jobs and "m" machines case, the number of solutions is $(n!)^m$ (which is 25 million for a five machine-five job problem).

Because of the enormity of the solution space, two enumerative optimal methods which list all possible schedules and then eliminate the non-optimal ones, were developed. These methods are (Bauer et.al. 1991, Liebowitz and Lightfoot 1993):

- Dynamic programming: this approach breaks down the scheduling problem into simple subproblems (nested problems) that are solved in a straight-forward fashion. The solution of one problem is then derived from the solution of the more simple preceding one. The main drawback of dynamic programming is, as in the above techniques, the amount of calculation time required.

- Branch and Bound method: this method creates an elimination tree which contains all possible permutations of the scheduling solution space. Those branches of the tree that do not approach the optimal solution are eliminated. However, to find an optimal solution can be costly in terms of computation time.

The final conclusion that can be drawn is that analytical approaches highly simplify the scheduling problem so that a final -optimal- solution can be produced in a relatively short computation time. The major drawback of this extensive simplification is that no general, practical scheduling solutions exist except for very specific situations and very small problems (simple manufacturing environments).

### 4.3 - Heuristic approaches

In the heuristic approaches the following terms are indistinctly used: dispatching rules, scheduling rules, heuristics and priority rules. They all mean the procedure employed to select the next job to be processed from a set of jobs awaiting service. Bauer et. al. (1991) define a heuristic rule as a "rule of thumb" that drastically limits the search for scheduling solutions in large problem spaces.

Some authors (e.g. Panwalkar and Iskander 1977, or Ramasesh 1990) make a distinction between priority rules, heuristics, and scheduling rules. Priority rule is considered a technique by which a value is assigned to each waiting job according to some method, the job being selected having minimum value. Heuristic is simply some "rule of thumb" (e.g. first-in-first-out), whereas a scheduling rule can consist of a combination of one or more priority rules or heuristics.

Another distinction is also made between simple heuristic rules and more complex ones (called heuristic programs). The latter ones are a combination of simple heuristics with a procedure for deriving a solution from them. This procedure is normally based either on backward scheduling from operation due dates, or on forward scheduling from operation start dates.

In general, heuristic approaches offer satisfactory solutions which are good enough most of the time and, due to the computation time required, they are able to solve realistic scheduling situations containing large and complex scheduling problems. Moreover, whereas analytical approaches do not permit the user interaction possibility (straightforwardly they give a solution from the input data), heuristic approaches -apart from simple heuristic rules- normally permit the communication with the user while developing the schedule, and eventually make use of his/her knowledge in order to make decisions.

### 4.3.1 - Classification of dispatching rules

Many authors have classified the dispatching rules according to different criteria (e.g. Wild 1984, Panwalkar and Iskander 1977, and Blackstone et.al. 1988):

- Rules involving the state of the shop:
  - » Local rules: depend solely on the data related to jobs in the queue of the machine.
  - » General rules: depend on data of jobs in other machines.
- Rules involving the time in the shop:
  - » Static rules: those in which the priority of a job does not change with the passage of time.
  - » Dynamic rules: the priority is function of the present time.
- According to the structure of the rules:
  - » Simple rules: are usually based on specific aspects of the jobs such as due date, processing time, remaining number of operations, etc..
  - » Combinatorial rules: the queue of jobs is divided into two or more groups with different rules applied to each one.
  - » Weighted index rules: these rules result from the combination of the first two but with different weights.
  - » Complex rules or heuristic programming: these are more complex procedures which may consider aspects like: alternate routing, machine loading, or alternate operation.
- According to the information contained (with some examples):
  - » Rules involving processing time: SI (shortest imminent operation time), LI (largest imminent operation time or truncated SI).
  - » Rules involving due dates: DD (earliest due date).
  - » Cost rules: Value (highest money value).
  - » Arrival times and random: FIFO (Frist-in-first-out), LIFO (Last-in-first-out), Random (select in random order), S-1 (least amount of slack).
  - » Setup time: NSUT (job that requires no setup).
  - » Machine: NINQ (select a job that will go to its next operation where the machine has the shortest queue).

Although it is impossible to identify any single rule as best in all circumstances, some of them have exhibited better performance in some studied manufacturing systems than others. Blackstone et.al. (1982) distinguish the following single rules as being the best overall: SI, Truncated SI, Earliest due date, least slack, least slack per operation, critical ratio, and FIFO.

### 4.3.2 - Bottleneck scheduling methods

The new trend in heuristic approaches are the so called "bottleneck scheduling methods" (Morton and Pentico 1993):

■ Myopic dispatch approach: this approach, whenever a machine becomes idle, schedules the available jobs by using a priority heuristic rule for *that single machine* (hence the name "myopic"). In this way, it creates the current machine schedules by sequencing the jobs forward in time.

The reason this approach is included in the group of the "bottleneck approaches" is because it treats the current machine as a bottleneck. For example, if the scheduling objective function is to reduce the total production lead time, then jobs will be prioritized in order to achieve the minimum completion time for the remaining operations. Another way of prioritizing jobs can be according to the total operation cost. In this case, jobs will be scheduled in the machine in order to achieve a minimum processing cost.

The major weakness of the myopic approach is that achieving local optimum does not assure the total optimum achievement. In particular, if downstream the current machine there is a strong bottleneck with very different priorities from the local ones, the myopic approach will be counter-productive.

■ Shifting bottleneck algorithm: the shifting bottleneck procedure is based on the nonlinear programming idea of holding all but one variable fixed and then optimise over that variable. Then hold all but a different one fixed, and so on. For a discrete problem containing a finite number of choices this method will converge to at least a local optimum in a finite number of iterations. Furthermore, if the one-variable optimization can be done in a decreasing order of importance, there is a higher possibility of the local optimum being the global optimum.

In the production scheduling problem, the sequence in which jobs are to be processed in a given machine corresponds to fixing the value of a variable. We hold the sequence on all machines but one fixed, and optimize the objective function by optimizing the sequence on the remaining machine. The fundamental bottleneck idea is that often only one machine greatly determines the final scheduling objective. Thus, if the problem is solved for the machine identified as the bottleneck -by using analytical or heuristic rules- with all other machines fully relaxed, a near optimum will be achieved in the scheduling objective.

The basic shifting bottleneck algorithm can be stated as follows:

1- Designate the machine with the highest cost as the primary bottleneck.

2- Solve exactly or heuristically the primary bottleneck problem.

3- Hold the primary bottleneck fixed, and check the cost on the other machines by also holding all but one of the remaining machines relaxed. This is done for each remaining machine in turn.

4- Identify the machine with the highest resulting cost as the secondary bottleneck.

5- Holding the secondary fixed, reoptimize the primary, then hold the primary fixed and reoptimize the secondary, and so on until there are no further improvements.

6- In a similar fashion find the third bottleneck and apply the same procedure.

■ Bottleneck dynamics: basically, bottleneck dynamics estimate the dynamic value of extra capacity for each resource (resource price), the dynamic value of having capacity earlier rather than later for each resource (resource delay cost), and delay prices (delay costs) for each activity within the shop.

Trading off the cost of delaying the activities versus the costs of using the resources allows calculating, for example, which activity has the highest benefit/cost ratio to be scheduled next at a resource, or which resource should be chosen to do an activity in order to minimize costs. These prices allow making local rather than global decisions with easy cost calculations. Further applications of the bottleneck dynamics method include: sequencing, routing, release and order timing, lot sizing, and batching.

■ OPT's scheduling approach: OPT scheduling software operational features and underlying principles will be thoroughly analyzed in chapter 9. The special attention OPT gives to production bottlenecks, forms the fundamental of the whole underlying scheduling principles.

## 4.4 - Artificial Intelligence

Artificial Intelligence (AI) is the science area that, using different programming languages and techniques, enables computers to mimic human reasoning and thinking processes. AI is concerned with the modelling of human decision-making actions, and has as ultimate goal the development of an intelligent machine that exhibits intelligence on the same order as that of a human and can itself make decisions.

Many authors have focused their attention on analysing the diverse implications of this relatively new technology (e.g. Arff et.al. 1991; Harmonosky and Robohn 1991; Ignizio 1991; Kanet and Adelsberger 1987; Kathawala 1990; Kerr 1992; Maus and Keyes 1991; Smith 1992).

### 4.4.1 - Artificial Intelligence-based searching methods

Artificial intelligence approaches represent the scheduling problem as the determination and satisfaction of the constraints that are found in the scheduling domain. AI is utilized to enlarge knowledge representation techniques to capture the constraints, integrate them into a search process, relax them when a conflict occurs, and diagnose poor solutions to the scheduling problem.

AI scheduling technology is based on the scheduling heuristic methods reviewed in the previous section (although in some cases scheduling heuristics can be combined with optimal mathematical solutions). Briefly, some of the techniques applied in AI are:

- Intensification/diversification methods: intensification strategy is used when the scheduling problem has certain structure and the best solution for it can be found. On the other hand, diversification strategy is employed when the problem has no structure at all and one of the tools utilized for getting out of the rut is random sampling. Modern scheduling techniques which employ intensification/diversification methods are: neighbourhood search, tabu search, simulated annealing, and genetic algorithms.

- Neural networks: this approach tries to simulate the learning process of the human brain. For a particular set of inputs that define the scheduling problem, there are suggested a set of actions. Several layers of very complicated networks are employed, allowing inputs to be added together, strengthened, or stopped.

- Beam search techniques: also called partial enumeration techniques, is a sort of branch-and-bound procedure, but instead of eliminating the part of the tree that is guaranteed useless, those parts that are likely to be useless are eliminated (requiring a precise definition of what "likely" means).

### 4.4.2 - Expert systems

Expert systems (also called knowledge-based systems or a rule-based systems) exhibit a degree of expertise in problem solving comparable to that of a human expert. Expert systems capture the expert knowledge of a human in specific domains, and translate it into a "thinking" computer machine through the use of scheduling heuristics.

The required knowledge consists of an association between decision-making conditions and problem solving actions encoded as a set of "If...Then" rules. Basically, knowledge acquisition and encoding of this knowledge into software modules are the two steps involved in the development of an expert system. As a result, expert systems applied to production scheduling, utilize various heuristic-based rules to search for a solution to the scheduling problem. However, expert systems do not employ new heuristic rules; they simply implement in a particular manner the common dispatching rules reviewed in the previous section.

## 4.5 - Simulation

Simulation is defined by Bauer et.al. (1991) as "the establishment of a mathematical logical model of a system and the experimental manipulation of it on the computer". Simulation depends on the description of the system in terms acceptable to the computer. To do this, it is necessary to define the state variables of the system and the procedure (or rule) that cause these variables to change over time. As the values of the variables change over time, the system effectively moves from state to state. Simulation is then the process of moving the system from state to state according to the rules that define the operational procedure of the system.

The application of simulation in manufacturing is mainly focused on production systems design (analytical models) and control/scheduling (operational models). In design, a replica of a real or hypothetical manufacturing system can be simulated on the computer so that system behaviour under different circumstances can be analyzed. The use of simulation as a control aid is normally used to analyze feasible production schedules. A schedule is generated by simulating the execution of the modelled manufacturing system under any selected heuristic rule (simple or complex), and taking the recorded execution history as the schedule. Then, the performance of alternative schedules -developed using some other logic- can be compared, and selected the one with the best performance. With this technique, potential plant bottlenecks or other material flow problems can be evaluated and resolved.

However, as in the case of Artificial Intelligence (expert systems), simulation approaches applied to scheduling do not implement new heuristic rules, but simply put the existing ones into practice to check their validity in solving specific production situations.

+ Simulation-based scheduling advantages

The main advantages of computer simulation are:

» The strongest point is that information about system performance is obtained prior to implementation, thus pinpointing the risks and benefits of the simulated system. Applied to scheduling, exploratory tests upon the produced schedules can be performed by changing slightly the environment situation (e.g. introducing a new machine, reducing workforce, introducing overtime, reducing the production quantity of some orders, etc..).

» Simulation provides a high modelling flexibility.

» With a computer model of a system, the element of time can be accelerated so that long-term effects can be simulated.

» Finally, the computer simulation approach, apart from being very useful in manufacturing, has an immense potential application area. For example in: medicine, electronics, education, large-scale military projects, and arcade games.

+ Simulation-based scheduling drawbacks

The disadvantages related to computer simulation are:

» The possibility of including all the state variables that define a real system is questionable, and may depend greatly on the capabilities of the computer software employed. Therefore, the results obtained from a simulation study can also be questionable.

» The accuracy of a simulated system depends as well on the judgement and skill of the programmer.

» Simulation-based approaches provide no reactive capabilities, except of running the simulation again after the cause of the problem has been corrected.

» Simulation is not an optimization technique (is based on heuristics). So an optimal solution is not guaranteed (only a satisfactory one).

» System behaviour simulation is costly not only in computer time, but also -and more important- in the time required for the programmer to create the model, experiment, and modify it.

» Annino and Russell (1981) identify seven most frequent causes of simulation analysis failure: failure to define an achievable goal, incomplete mix of essential skills, inadequate level of user participation, inappropriate level of detail, inappropriate language, using an unverified or invalid model, failure to use modern tools and techniques.

**4.6 - Last comment**

DISASTER and OPT scheduling softwares are both based on the "Drum-Buffer-Rope" technique and are clear examples of bottleneck scheduling approaches. They both focus on the system constraints to manage the shop floor operations and subordinate the rest of the resources to their optimal schedules.

In a study performed by Neely and Byrne (1992), a particular application of bottleneck scheduling was compared with six simple heuristic rules (e.g. FIFO, total operation time, batch operation time -higher priority assigned to the batch with shortest operation time-, etc..). The final results showed that there was a trend for throughput to increase and inventory to decrease when bottleneck scheduling was used (this case will be reviewed in more detail in chapter 8).

# 5 - GENERAL PRODUCTION SCHEDULING PRINCIPLES

Extracted from previous chapters, some general statements related to production scheduling can be drawn. These statements, that form what can be considered "general scheduling principles", are presented divided into three different hierarchical levels:

- General problem solving approach.
- General scheduling aims.
- Operational scheduling principles.

## 5.1 - General problem solving approach

**Principle - 1:** <u>There is no universal scheduling solution</u>.

The variety of the scheduling problems form such a wide domain that no general, effective scheduling technique can answer to all of them. Besides, each manufacturing system exhibits its own attributes that make it unique among the rest of the systems. Even same production systems will have different behaviours according to particular management style, company goals, or performance measures.

Furthermore, the development of a general scheduling problem solving approach is destined to fail due to: (a) massive data requirements, (b) cumbersome output, (c) impossibility to comprise all the possible scheduling situations, (d) slow execution, or (e) the mistrust of the schedulers.

## 5.2 - General scheduling aims

**Principle - 2:** A feasible schedule cannot contain any conflict between the constraints of the system.

All systems are characterized by the existence of two types of constraints (Froeschl 1993):

» Fixed/hard constraints: these are the physical and technological constraints formed as a result of the production and product structure. Examples of fixed constraints are: production routings including operation precedences (one operation can only be performed when the previous one has finished), number and variety of products, No. of resources, number of operators, etc..

» Soft constraints: these type of constraints can be dynamically adjusted -within limits- to the production requirements. They comprise temporal constraints regarding, for example, the orders to be scheduled (e.g. earliest start date and due date) and to temporal capacity restrictions (such as regular work time).

Jobs to be scheduled should be assigned to the available resources in a way that all constraints are obeyed. The schedules that obey all imposed constraints and do not contain any logical contradictions which prove then impossible to follow before they are released to the shop floor, are termed feasible. Violation of hard constraints invalidates definitively the schedule; while violation of soft constraints can -in the best of the cases- lead to poor schedule performance (e.g. late orders, WIP increase, overtime requirement, etc..).

**Principle - 3:** System disturbances must be taken into account while developing a schedule.

Production systems can be divided into two parts:

» Static part. Is formed by the product and production structure in which hard constraints are included. The static part can be considered fixed in time, although in a medium/long term horizon, changes can take place (e.g. new resource investment, introduction of new products, change of process routings, etc.).

» Dynamic part. Embraces dynamic events like production disturbances, dynamic orders (with possible changes in due date, priority and amount), and dynamic demand. Some of these events can be predicted (e.g. planned maintenance, seasonal demand), while others are completely unpredictable (e.g. machine breakdowns).

In creating a feasible schedule, apart from obeying hard and soft constraints, the unpredictable events contained in all production systems have to be somehow handled. The schedule should be safeguarded or immunized to a certain level of uncertainty.

As Berry (1993) states, "..scheduling is essentially a problem of decision-making under uncertainty and, as such, uncertainty is a key factor in both schedule representation and generation".

There are two possible ways of addressing systems unpredictability:

- *Modify the system in order to simplify the scheduling problem.*

Previous to the installation of any particular scheduling method, changes in the static part of the system can be arranged in order to facilitate the scheduling task. Some of these changes could be: simplify the production process, change the plant lay out, reduce the batch sizes, reduce set-up times, install real time control systems, install management tools for quick response to production events, etc..

Bielli and Dell'Olmo (1993) maintain that with the appropriate lay out, efficient material flow and an efficient material handling system, production control and scheduling would be much easier. Additionally, in what Burbidge (1985) calls "Law of Material Flow", he argues that the efficiency of a production system is inversely proportional to the complexity of its material flow system. According to him, simple material flow systems should be designed based on Product organization and thus restrict the freedom of decision choice in Production Planning, to the limited extent needed to maintain the simple system.

However, there are some environments in which redesigning the whole system may not bring the desired benefits. For example, in manufacturing systems characterized by unpredictable demand, unpredictable process times, or containing dynamic events (orders, production disturbances), continual rescheduling would take place. Any attempt to maintain the schedule untouched would require a constant scheduler and foremen dedication in solving the continual production problems encountered.

■ *protect the schedule against production disturbances.*

The alternative to the above expensive and time consuming solution, is to incorporate in the schedule an uncertainty factor. In this case, the production system does not suffer any modification, and is the scheduling system the one that addresses the unpredictability element. It must be said that this is the most common way of tackling production disturbances.

Schedules are normally protected by: (a) introducing inventory in key parts of the manufacturing system (i.e. "safety stock"), and (b) reserving part of the resources capacity to utilize the "catch up" possibility when production disturbances arise. Capacity can be reserved whether introducing slack time or queue time in the process time, or loading in the scheduling system lower human and resource capacity than the one really available.

**Principle - 4:** Schedules must be evaluated according to the achievement of certain objective(s)/goal(s).

In addition to schedule feasibility and the consideration of the uncertainty element, schedules should be evaluated according to some criterion of efficiency or the achievement of certain objective function (Berry, 1993; Froeschl, 1993; Smith et. al., 1990; Vollmann, 1992). According to Froeschl (1993), scheduling goals can be stated either in a quantifying objective (i.e. economic goal expressed in terms of performance measures) or in terms of preference rules that order the possible schedule alternatives by some measure of utility. Additionally, the objectives can also be stated in customer satisfaction terms (e.g. meet due dates, produce quality products) or in operational terms (e.g. minimize inventories, minimize costs, minimize lead times, and optimize equipment, raw material, and operators utilization).

### 5.3 - Operational scheduling principles

**Principle - 5:** There must be a match between the scheduling technique and the production environment.

The appropriateness of a scheduling approach should be assessed by how well its assumptions correlate with the characteristics of specific production environments. The selected scheduling system should be capable of realistically represent the following production features:

» Management policies (e.g. overtime utilization, set up saving procedures, performance measures, etc..).

» Management style (e.g. production management philosophy)

» Production objective/goal.

» Static elements: accurate factory model.

» Dynamic elements: realistic representation of the dynamic aspects.

For example, manufacturing systems dominated by dynamic events will require flexible scheduling tools and user interaction capabilities to permit quick respond to schedule changes. While in stable and predictable production situations, more static scheduling tools can be applied and seek the achievement of the best scheduling solution.

**Principle - 6:** Unless there is a simple scheduling problem -in which case analytical methods can be used- heuristic approaches will be utilized.

Most of the manufacturing systems are characterized by complex scheduling situations in which analytical tools would be totally impractical (due to the long computer time they require). However, if the scheduling problem is so complex that optimum schedules cannot be found, then heuristic methods that do not guarantee the best solution would have to be employed. In this case, the user should try to find the heuristic technique that better depicts the scheduling goal and correlate with the characteristics of the production system. French (1982) maintains that "if the best scheduling solution cannot be found, then a schedule that performs better than average should be set".

**Principle - 7:** Optimising isolated parts of a system does not necessarily produce an optimum solution for the whole system.

Sometimes, specific objectives may be in conflict with overall system goals. For example, if the final goal is to achieve due date performance, then, the application of efficiency incentives will -probably-: (1) increase overall inventory (resources will tend to be busy all the time), (2) increase production lead time, and (c) miss customer due dates.

Another example of conflicting objectives can be originated when independent schedules are produced for isolated areas of the system (e.g. FMS, resource constraints). This schedules can have particular goals that may be in conflict with the global ones.

Therefore, The scheduling approach should have a holistic view of the system, so that suboptimization and conflicting objectives are avoided. Burbidge (1985) states in what he calls the "Law of Gestalt" that "the whole is not the sum of its parts", and by extension that "a set of sub-optimum solutions can never produce a true optimum solution".

Table 5.1 summarizes the general production scheduling principles that have been discussed.

| | |
|---|---|
| GENERAL PROBLEM SOLVING APPROACH | 1- There is no universal scheduling solution. |
| GENERAL SCHEDULING AIMS | 2- A feasible schedule cannot contain any conflict between the constraints of the system.<br><br>3- System disturbances should be taken into account while developing a schedule:<br><br>» Modify the system in order to simplify the scheduling problem.<br>» Protect the schedule against unpredictable events.<br><br>4- Schedules must be evaluated according to the achievement of certain objective(s)/goal(s) . |
| OPERATIONAL SCHEDULING PRINCIPLES | 5- There must be a match between the scheduling technique and the production environment. The following features should be contemplated by the scheduling system:<br><br>» Management policies and style.<br>» Production objective/goal.<br>» Static elements.<br>» Dynamic elements.<br><br>6- Unless there is a simple scheduling problem -in which case analytical methods can be used-, heuristic approaches will be utilized.<br><br>7- Optimising isolated parts of the system does not necessarily produce an optimum solution for the whole system. |

**Table 5.1**: General Production Scheduling Principles

# 6 - THEORY OF CONSTRAINTS (TOC)

## 6.1 - Overview of TOC's concepts

The Theory of Constraints (TOC) management philosophy was created in the late 1970s by Eliyahu M. Goldratt and is founded on the assumption that the primary goal for any business is (Goldratt and Cox 1984): "To make more money now as well as in the future". To attain this goal, TOC tries to efficiently manage the shop floor operations by focusing on the constraints of the system and subordinating the whole plant to their optimum schedules.

TOC seeks to achieve a fast and smooth production flow by synchronizing the manufacturing operations. This synchronized manufacturing is achieved by paying special attention to the detailed production scheduling task (bottleneck/non-bottlenecks, 9 scheduling rules, "Drum-Buffer-Rope" (DBR), and the DBR-based OPT and DISASTER scheduling softwares) and handling effectively production disturbances (production phenomena, Buffer Management). Further production management concepts included in TOC are: (a) the statement of the goal in operational and financial terms and the local performance measurements employed to control the shop floor operations, (b) the Process of On Going Improvement (POOGI) concept that asserts that the company should be continually moving towards the goal by improving the key parts of the organization (the constraints), and (c) the V-A-T plant classification with their particular characteristics and production problems.

In addition, TOC can also be seen as a general problem solving approach through the application of the "5 focusing steps" and the "Thinking Process" methodologies that enable the organization identify their constraining elements (internal or external constraint) and improve their overall performance by "breaking" them.

This chapter reviews all these different TOC concepts in the following order (see summary of the TOC parts in Figure 6.1):

- TOC goal, objectives and basic assumption
- Constraints, bottlenecks and CCRs
- General problem solving approaches (the 5 focusing steps and the Thinking Process).
- Production management concepts (operational and financial measures, Throughput World, local performance measures, production phenomena, Buffer Management, V-A-T plants, 9 scheduling rules, and Drum-Buffer-Rope).

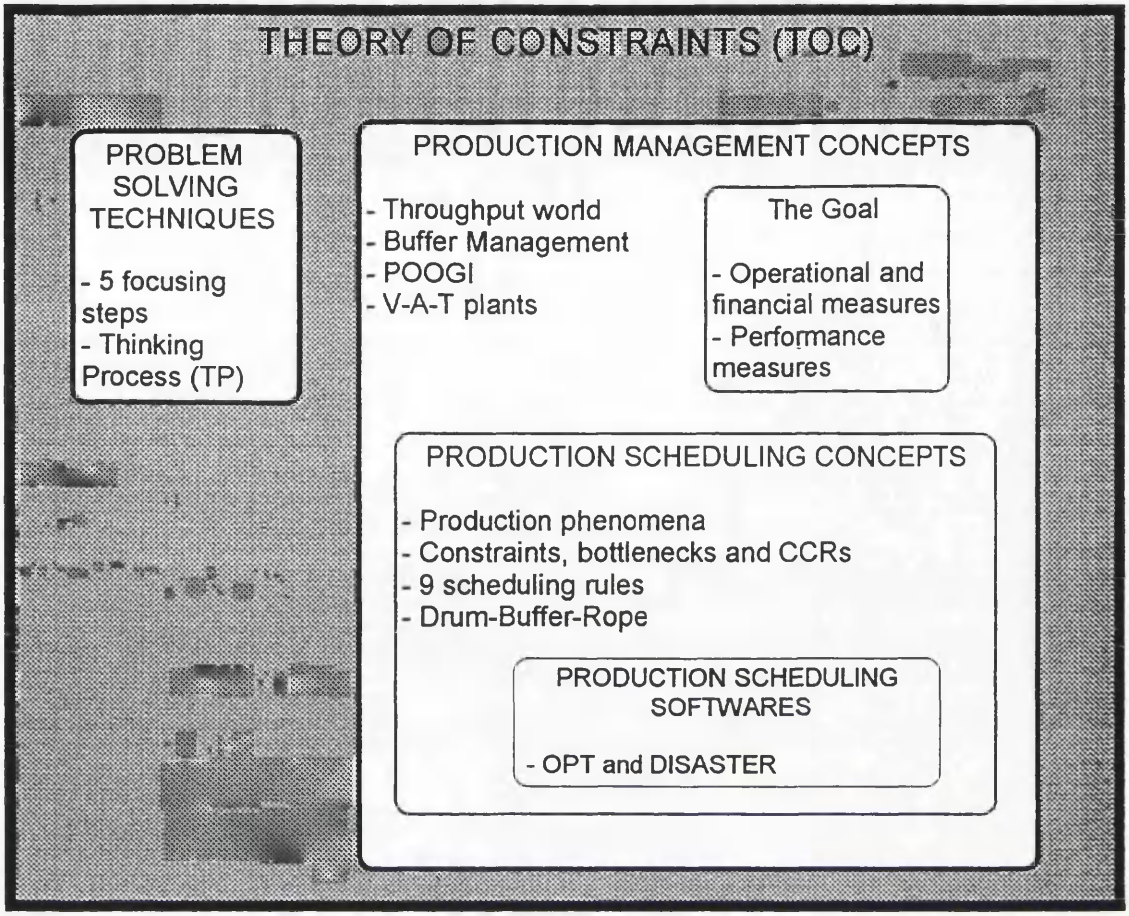



**Figure 6.1:** TOC parts

### 6.2 - TOC evolution

The evolution of the Theory of Constraints philosophy has been very fast since it started to emerge in the late 1970s. New theories and perceptions of the production insights are still now being created; giving the impression that TOC is still growing.

In its early days, it started as a production scheduling software called OPT. This software contained particular production management concepts that were revolutionary for that time. Then, the theoretical aspect of OPT started to emerge, and the Theory of Constraints was formulated. At the beginning, TOC was mainly focused on the production aspect of the organization, but in the last 5 years, it has concentrated on spreading its principles to the whole enterprise with the aid of the Thinking Process (TP) called "soft system".

This last phase of the TOC evolution is not widely known, but the previous rapid grow has created some confusion about the terms to be employed to refer to all the theories and scheduling concepts. For example, Ronen and Starr (1990) call "BIG OPT" to TOC's managerial principles and "SMALL OPT" to the scheduling mechanisms. Others simply use OPT to refer to the production management concepts, and TOC to the TP. In this text, OPT software will be differentiated from the production management and scheduling concepts (that are going to be referred as TOC), and from TP.

OPT/TOC evolution contains the following stages:

» OPT creation: in the late 1970s, Eliyahu M. Goldratt created a scheduling software named Optimized Production Timetable (OPT). The name of Optimized Production Timetable was changed to Optimized Production Technology a few years later. This initial software contained an innovative data structure that permitted high computational speeds.

» Production management concepts start to emerge: in 1980 and 1981, the first new ideas about the production insights started to emerge. In 1981, Goldratt published a paper recognizing the existence of excess capacity in the system and how production disturbances (embraced in two concepts: initially called "non-determinance" and "interdependence", and later "statistical fluctuations" and "dependent events") do not permit a plant to be balanced.

Later, production bottlenecks were separated from non-bottlenecks and a crusade against traditional cost accounting was undertaken (Goldratt 1983). Finally, a marketing campaign was launched -via published papers- that exposed OPT software successful applications.

» The success of "The Goal": In 1984, Goldratt and Cox wrote "The Goal". This book, explained the initial production management concepts and the Drum-Buffer-Rope scheduling technique. It was a total success and turned out to be a bestseller (1.3 million copies have been sold worldwide). Many managers around the world read the book and started to apply the TOC principles. As a result, even simple manual DBR applications (without the aid of the OPT software) provided benefits to many companies.

» TOC philosophy continued to grow: in 1985, the distinction between production bottlenecks and Capacity Constrained Resources (CCR) was stated (Goldratt 1988). Similarly, the crusade against traditional cost accounting carried on (Goldratt 1985).

In 1986, Goldratt and Fox wrote "The Race". This book explained in more detail all the TOC concepts contained in "The Goal", but it did not achieve the same success. Furthermore, "The Race" analyzed what was claimed to be the missing link between scheduling and process improvement: the Buffer Management (BM) technique.

At the end of 1986, TOC's 5 focusing steps were stated and the evolution of the philosophy as a production management approach seemed to be finished (Goldratt 1988).

» TOC concepts extended to other areas of the organization: once the TOC application in the production area seemed to be finished, the Avraham Goldratt Institute (AGI) -source of all TOC management theories- tried to extend TOC to other areas of the organization (e.g. marketing, purchasing, etc..). The Thinking Process (TP) problem analysis methodology was created to address this new challenge. Goldratt published the book "What is this thing called TOC and how should it be implemented?" in 1990. Part of the TP methodology was explained in that book.

» TP, the final answer: nowadays, AGI (with Goldratt as the founder of it) presents TP as the general problem solving approach that would set the company in a Process of Ongoing Improvement (POOGI). In November 1994, Goldratt will publish the book "It's Not Luck" in which the story of "The Goal" is continued but with the introduction of the new TP ideas.

### 6.3 - TOC goal, objectives and basic assumption

TOC maintains (Goldratt and Fox 1986) that a company may seek to: achieve better customer service, increase the market share, lower production costs, improve the quality, etc.. All these targets may be useful means to the goal of the company, but -according to Goldratt- they themselves are not the goal. The single goal for a manufacturing company is: *to make money in the present as well as in the future.*

To achieve the goal, the company must embark in a Process of Ongoing Improvement (POOGI) through synchronized manufacturing. Synchronized manufacturing is any method capable of moving material quickly and smoothly through the production processes in response to market demand. TOC attempts to achieve synchronization by managing effectively the constraint resources (i.e. achieve maximum throughput while simultaneously minimizing inventory and operating expenses) by applying the DBR scheduling technique.

The POOGI is established by:

1- Periodically re-evaluating the competitive environment, re-examining the firm's competitive position, and re-synchronizing the manufacturing system (due to the dynamic character of manufacturing systems) (Fawcett and Pearson 1991).

2- Applying the Buffer Management technique that not only serves as a throughput protection tool but also provides essential information regarding production disturbances.

3- Solving the sources of disruptions by installing preventive maintenance, quality improvement tools, set up reduction mechanisms, etc..

The Avraham Goldratt Institute -AGI- now declares that the TP methodology represents the mechanism that would embark the company in a Process of on Going Improvement -POOGI- (AGI Production Workshop notes) by (a) helping identify the resource capacity and intangible constraints of the system, and (b) providing the logical tools to find the best solutions to the major organization problems.

Finally, the primary characteristic of the TOC management philosophy is its holistic view of the systems. The basic TOC assumption is that *the sum of local optimums is not equal to the global optimum.* This assumption is in conflict with many managerial beliefs based on the traditional cost accounting method.

### 6.4 - Constraints, bottlenecks and CCRs

As it has already been stated, the constraints of the system represent the fundamental element from which the whole TOC philosophy has been built. Umble and Srikanth (1990) define "constraint" as "..any element that prevents the system from achieving the goal of making more money". They also, identify the following types of constraints:

» Market (external) constraints: the demands of the marketplace determine the throughput boundaries within which the firm should operate.

» Material constraints: these type of constraints arise when there is a lack of the necessary raw material or WIP in order to keep the production process flowing.

» Logistical constraints: this type of constraints refer to any constraint that is inherent to the manufacturing planning and control system. Their primary influence is that they obstruct the smooth flow of goods through the system. Examples of this sort of constraints are (a) long order generation times at a planning level, or (b) material control systems with monthly time buckets in which the visibility of the order due dates is lost.

» Managerial (intangible/policy) constraints: these constraints represent the management strategies and policies that adversely affect the decisions related to manufacturing. In many cases, managerial constraints are the result of a lack of understanding of the factors that enhance or detract from a synchronous operation.

Determining batch sizes by using economic order quantities (EOQ), using the utilization of resources as a performance measure, and applying efficiency incentives are three examples of policy constraints.

» Behavioral constraints: these constraints can also be considered intangible, and refer to the attitudes and behaviours exhibited by the workforce. Behavioral constraints may be generated from the work habits, practices, and attitudes of the managers or workers, and can act counter to the achievement of a fast and smooth production flow. One example of this type of constraint is the "keep busy" attitude often exhibited by many supervisors and workers.

» Capacity constraints: These constraints (normally called capacity constrained resources, or simply, CCRs) take place when the available capacity at a resource is insufficient to meet the workload demand places on it. When the constraint is located in the manufacturing system, the operation with the least relative capacity will dictate the capacity level and responsiveness of the entire production system. The result is a disruption in the material flow.

Other authors have also focused their attention on classifying the different types of constraints. Fawcett and Pearson (1991), for example, divide the constraints in two groups: (1) external constraints (are those governed by market characteristics and beyond the control of the organization), and (2) internal constraints (which include limited capacity at the resources, inflexible work rules, limited labour skills, and particular management philosophy).

Ronen and Spector (1992) identify three types of constraints: (a) faulty (dummy) internal constraint (the constraint resource originated as a result of inadequate policies), (b) plausible internal constraint (the resource with less relative capacity of the whole manufacturing system), and (c) market constraint (the situation of production demand being less than the system production capacity).

Finally Cohen (1988) identifies four different constraints: capacity, market, material and management policy.

+ Bottleneck and non-bottleneck resources

A bottleneck resource (or simply bottleneck) is any resource whose capacity is equal to or less than the demand placed on it. In contrast, non-bottlenecks are those resources whose capacity is greater than the demand placed on them.

The bottleneck and CCR concepts have been equally employed by many authors and can sometimes cause certain confusion. Their difference lies in the fact that bottlenecks always contain less capacity than the demand placed on them. Management thus have to decide on the product mix that would bring the maximum profits. CCR's, on the other hand, are the resources that have the least relative capacity of the whole system (that can be more, or less than the demand placed on it); being utilized to govern the production flow. As a consequence, it is possible to have bottlenecks that are not CCRs (when there is lack of overall capacity in the system); and to have a CCR that is not a bottleneck (when there is excess capacity in the system). According to Goldratt and Fox (1986) and Frizelle (1989), experience suggest that most of the plants will not have more than two or three CCRs.

Additionally, the "moving bottleneck" phenomena takes place whenever changes in product mix or batch policies alter the location of the CCRs or bottlenecks (having to change the production management actions accordingly). Finally, "temporary bottlenecks" can also arise in the system. This phenomena originates as a consequence of momentary overloads caused by: unrealistic schedules, "end of the month syndrome", large batch sizes, or managerial policies.

## 6.5 - General problem solving approaches

The two general problem solving approaches explained in the following sections seek the identification of the organization constraints (core problems) and their optimal exploitation ('break') in order to achieve overall improvements that would affect their goals (e.g. manufacturing systems: "make money"; service organizations -e.g. hospitals-: improve the service quality; defence organizations: provide maximum security; etc..).

### 6.5.1 - The 5 focusing steps TOC decision process

The TOC philosophy formulates the 5 focusing steps called generic decision process as formed of the following stages (Cohen 1988, Fogarty and Blackstone 1991, Fox 1987, Goldratt 1990b):

1- Identify the system constraint(s): the first step of the decision process -or problem solving approach- is to identify the constraint of the system. This can be an external constraint (market), or an internal constraint (CCR, policy, material, etc..). The procedures to identify the CCRs are associated mainly with the type of manufacturing system, but some of the methods commonly employed are:

- Identify the locations where inventory accumulates.
- Look for late-expedite patterns.
- Identify late orders.
- Check due date performance.
- Analyze finished goods inventory profile.
- Calculate process loads and compare them with available capacity.
- Check frequency and number of breakdowns and set ups.

2- Decide how to exploit the system constraint(s): if the market has been identified as the constraint of the system, then there is excess capacity that can be utilized to (1) reduce overall WIP and, as a consequence, reduce production lead times, (2) meet customer due dates, and (3) improve customer service in order to attain more orders in the future.

On the other hand, if there is a CCR in the system it must be checked whether it is a bottleneck or a non-bottleneck.:

» If the CCR is a non-bottleneck, a particular schedule meeting customer due dates and including some measures of protection against production disturbances should be created.

» If the CCR is a bottleneck, an initial profitability analysis of the product mix should be done, and the most profitable products scheduled. Similarly, the bottleneck must also be protected against production disturbances.

3- Subordinate everything else to the above decision: in the case of an internal constraint resource, the rest of the plant should be subordinated to meet the schedule created for the constraint, and at the same time utilize the minimum inventory possible. Overall inventory is kept to a minimum by releasing material into the plant according to the needs of the constraint and allowing sufficient time for the material to arrive at its destination. In this way, the whole manufacturing system process the products at the rate dictated by the constraint, and due date performance is achieved with minimum overall inventory. Drum-Buffer-Rope (DBR) is the technique utilized to create the production schedules for the constraints and subordinate the rest of the resources to it.

4- Elevate the system constraint(s): in the case of the constraint being in the market, it can only be "elevated" employing the following actions to increase the number of orders: launch a marketing campaign, reduce final product prices, improve customer service by increasing quality or reducing lead times, etc..

On the other hand, if there is a CCR in the system (and specially if it is a bottleneck), its capacity can be increased by:

- Assuring that the CCR is running during the entire shift.
- Scheduling lunch times and breaks when the constraint resource does not need worker supervision.
- Subcontracting CCR's work.
- Allocating overtime or introducing an additional shift.
- Improving tools or gauges used at the CCR.
- Applying preventive maintenance to reduce downtimes.
- Reducing set up times.
- Inspecting the parts to be processed at the CCR to be sure that their quality is in accordance with the standards.
- Assuring that parts that have been processed at the CCR are not scraped later.
- Improving CCR's process by applying process engineering.
- Redesigning some products to be processed in other resources.
- Offloading CCR's work to other resources.
- Etc.

Finally, if a policy or other intangible factor is identified as the constraint of the system, the Thinking Process should be used to identify the best actions to take in order to "break" it.

5- <u>If, in the previous steps, a constraint has been broken, go back to step one, but do not allow inertia to be the system constraint</u>: this final focusing step warns that once demand has increased, or CCR's capacity has been elevated, the constraint will probably move to another part of the system (or outside). The organization should start again with the 5 focusing steps decision process in order to carry on with the Process of Ongoing Improvement (POOGI).

According to Goldratt (1990b), it turns out, that in most cases, the company does not bother to go back and start again with the process from the beginning (inertia in the attitude plays its role). In these cases, a dangerous policy constraint has appeared that has to be properly tackled.

### 6.5.2 - Thinking Process: TOC's latest development

TOC's "Drum-Buffer-Rope" approach for logistics management or Buffer Management production control technique must be considered as hard systems in the sense that they give particular solutions to specific production problems (they are "packaged" solutions applied to solve individual production problems). Hard systems lack a systems problem understanding aspect, and simply contemplate the techniques and methods required to solve commonly encountered problems. Additionally, hard systems are normally associated with (Stratton -1990- internal paper): work study techniques, simulation, statistical analysis, linear programming, goal programming, etc..

On the contrary, "soft systems" are developed to address system environments that do not lend themselves define clear objectives or cause and effect relationships. Such systems have been classified as "human activity systems".

It seems that there is a new tendency to improve the manufacturing systems by addressing the needs of the social aspects of the organization with the use of soft systems.

When TOC was finally formulated in 1986, AGI's emphasis started to be more focused on developing a thinking process together with tools and techniques to enable a POOGI. The Thinking Process (TP) soft system (also called "socratic method") started to be developed around 1988. TP applies the following tools to answer to what TOC considers now the new focusing process (Goldratt 1990a, AGI workshop description 1992, AGI production workshop notes):

1- <u>What to change?</u>

» The "Current Reality Tree" is the logical tool employed at this stage to pinpoint the core problems. This is achieved by connecting the production undesirable effects (e.g. high inventories, long lead times, excessive overtime) through cause and effect relationships. Once all the undesirable effects have been logically connected, the cause of approximately the 70% of the undesirable effects is identified as the core problem.

2- <u>To what to change to?</u>

» "Evaporating cloud" represents the thinking process that enables present the conflicts that originate the core problem, and then directs the search for a solution through challenging the assumptions underlying the conflict. The "injection" that would solve the core problem is identified by this method.

» "Future Reality Tree". Starting from the identified injection, a solution is constructed which, once implemented, would replace the existing undesirable effects by desirable effects without creating devastating new ones.

3- How to cause the change?

» The "Prerequisite Tree" points out logically the obstacles that would be encountered in applying the injections, and the intermediate objectives that have to be achieved in order to successfully apply the injections.

» The "Transition Tree" is the final tool employed to construct a detailed implementation plan that would allow application of the suggested injections and finally solve the core problems.

The sequential application of the cause and effect trees will -according to TP- serve to (a) identify the constraint of the system (also called "core problem"), and (b) embark the company in the POOGI (by starting again from the first step when former constraints are broken, and providing new solutions to current constraints). Finally, the TP methodology should be understood as formed of the effect-cause-effect trees and the "evaporating cloud" technique that determine the actions to be take in order to turn the production undesirable effects into desirable effects.

### 6.6 - Production management concepts

The goal for a manufacturing system and the general problem solving approaches have already been stated. However, there are still further TOC production management concepts that enable (a) the measurement of the impact which undertaken actions have on the goal, (b) the protection of the system from production disturbances, (c) the categorization of the production environments, and (d) the achievement of a synchronized manufacturing through an efficient management of shop floor operations ("bottom up" approach).

#### 6.6.1 - Operational and Financial measures

The indicators of the organization effectiveness in achieving the goal are: Net Profit (NP), Return on Investment (ROI), and Cash Flow. However, to relate the day to day operational decisions to these financial measures, it is necessary to have so-called operational measures that relate to bottom line performance.

The operational measures would be able to show the way the company is moving towards the goal by answering:

1- How much money has to be put in the company? (Operating Expense).

2- How much do we get out of the company? (Throughput).

3- What is the value of the company? (Inventory).

These operational measures can be properly defined as (Johnson 1990):

- Throughput: the rate at which the company makes money through sales.
- Inventory: all the money that the system has invested in purchasing things which it intends to sell (avoiding added value).
- Operating expense: all the money that the system spends in order to turn inventory into throughput.

According to these definitions: (a) NP=T-OE and (b) ROI=(T-OE)/I. Increasing Throughput or reducing Operating Expenses the three financial measures increase. However, whilst both ROI and Cash Flow are improved by reducing Inventory, there is no direct effect on Net Profit. The increase in Net Profit is obtained indirectly from the carrying cost (i.e. financial cost, storing cost, handling cost, etc..) reflected in the Operating Expenses.

The total relationship between the operational measures and the financial measures is shown in Figure 6.2.

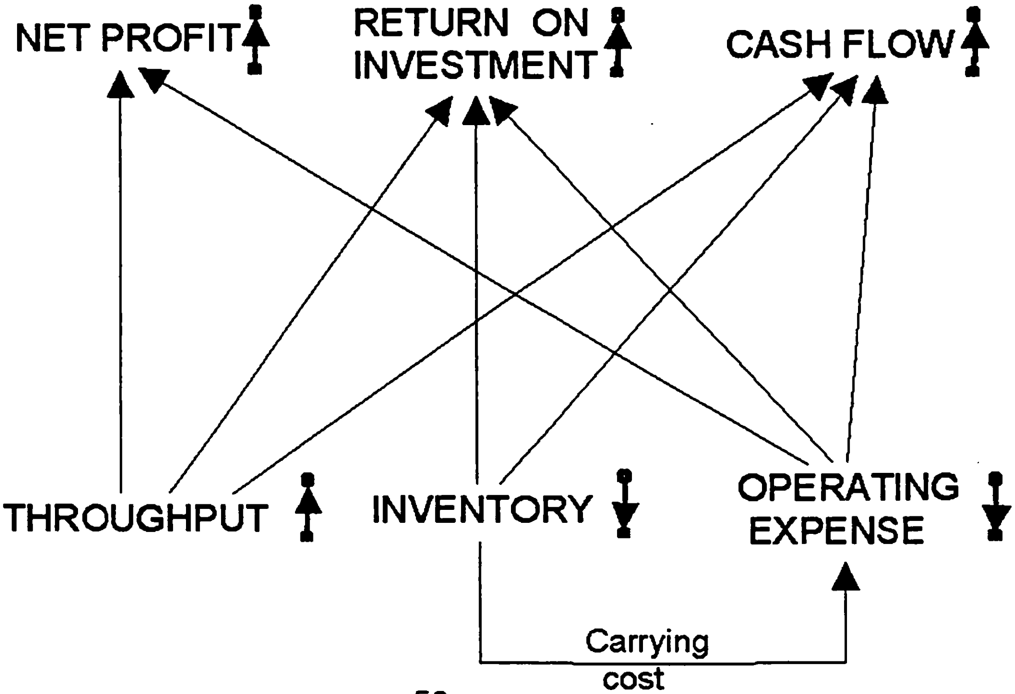





**Figure 6.2**: impact of the operational measures on the finanacial measures

### 6.6.2 - Cost world vs Throughput world

From the relationships that have just been defined, many managers applying the traditional cost accounting performance measures (in which cost per part reductions and local efficiencies achievement are two of the basic principles -Goldratt 1983-) will choose Operating Expenses reduction as the first action to be taken in order to achieve the goal (Goldratt 1990a). Throughput is often regarded as the second priority (this is because people are slow to realize its influence in financial measures). While, inventory reduction will be the last in the list. This is a typical way of acting in the "COST WORLD" (AGI Production Workshop notes, Goldratt 1990a).

In contrast to the "Cost World", TOC includes the "Throughput World" concept. In this case, the increase of Throughput becomes the first priority; with inventory and operating expenses in second and third place. The reason stands in the extent to which the way constraints in TOC represent those in the real organization.

If the organization is considered as a chain (a series of departments with their particular functions through which the work flows), Throughput is considered as the strength of the chain. The strength of the chain is determined by its weakest link (Throughput, as being the rate at which work flows from the end of the chain, depends on the performance of the slowest department/function). In the "Cost World", reducing operating expenses is analogous to reducing the weight of the chain (Throughput). While in the "Throughput World", focusing on increasing throughput in the weakest link of the chain is analogous to increasing throughput in the whole system.

### 6.6.3 - Local performance measurements

Utilization and efficiency are used by traditional cost accounting to measure the performance of a resource or department. The underlying assumption of these performance measures is that system output will be maximized if each resource output is maximized. TOC has demonstrated that non-CCRs should produce only in quantities to supply the constraint. Activating a non-CCR at 100% of its capacity would not only fail to provide any benefit, but rather it will increase WIP and will be in contradiction with the goal.

The alternative to this problem is to institute local performance measures that will induce the departments to do what is right for the company as a whole (Goldratt 1988, 1990b). The two local performance measures proposed by the TOC management philosophy are:

» Inventory dollar-days: they are designed to measure the extent to which a department or worker contributed to the early finish of an order. If an order has reached the constraint earlier than the time defined as a buffer, all areas responsible for the early processing of material will receive a penalty. The penalty would be the material expense of the inventory multiplied for the number of days until the material should have reached the constraint. The stockroom and each resource that has worked on the material before the proper release date would be penalized. With this measure, workers would be certain that the materials are not processed before they are due.

» Throughput dollar-days: they charge the resources that are still processing the parts that should have been halfway into the time buffer. The penalty is the value of the order to which the parts belong multiplied by the number of days that have passed since the buffer midpoint.

This measure also addresses quality problems in the sense that if a worker would want to finish a part quickly to avoid penalty, any defect would be charged throughput dollar-days until the defect is removed through rework or replacement.

The two local performance measurements provide an incentive for workers to follow the schedule and to work quickly and carefully. They are consistent performance measures in the sense that they are properly aligned with global financial objectives.

### 6.6.4 - Production phenomena

In 1981, Goldratt states in his article "The unbalanced plant" that due to the coupled effect of what he called non-determinance and interdependence the achievement of a truly balanced plant that would lead to rapid bankruptcy is avoided. Non-determinance stands for the unreliable character of the information fed into the schedule caused by the inherent variability of the operation times. This factor added to resources interdependence (technology constraints make that one operation can only be done when a previous one has been completed) lead to fluctuations at each stage be passed on to the next stage. As a result, deviations from schedule will accumulate from stage to stage as one passes downstream in the production process.

These two features -present in all manufacturing systems- are later related as production phenomena (Goldratt 1990a, 1990b), and named:

» Statistical fluctuations: represent the stochastic nature of the production process, and are present in process times, set up times, percentage of scrap, yields, and so forth. Additionally, unpredictable events like machine and tool breakdowns, worker absenteeism, vendor late delivery, customer-required change, etc.. introduce an additional disruptive effect in the system.

» Dependent events: dependency enters in the manufacturing process when operations have to be performed sequentially. This phenomena influences throughput because of the existence of CCRs in the system that limit the maximum output that can be achieved.

The combined effect of statistical fluctuations and dependent events manifest themselves as disruptions in the production system that, if not properly handled, will cause an increase in WIP and lead times, and a reduction in throughput. There are two possible ways of decreasing the effect of the production phenomena: (1) introducing buffers into the system, and (2) reducing the variability associated with the production process.

### 6.6.5 - Buffer Management

+ Types of buffers

Buffers are utilized to decouple critical resources of the production process from the uncertainty associated with preceding resources resulting from statistical fluctuations and dependent events. The types of buffers that can be employed are:

- Inventory (safety) buffers: these buffers contain a limited number of products located in front of key resources.

- Time buffers: this type of buffer is applied in the DBR scheduling technique. A time buffer is based on the amount of time the critical resource needs to be covered against the effect of production disturbances. The size of the time buffer will primarily depend on the excess capacity of the non-CCRs that precede the CCR and on the severity of the production disturbances.

TOC recognizes three time buffers categories:

- Capacity constraint buffer: is located in front of the constraint.

- Assembly buffer: is placed in front assembly points to ensure that parts processed by the CCR are not blocked in front of assembly operations waiting for parts processed in non-CCRs.

- Shipping buffers: represents the protection placed before shipping in order to achieve on time deliveries for those products that do not contain any CCR in their routes.

+ Buffer Management

Buffer Management (BM) is the shop floor production control method that assess the state of the work in process compared to the planned state and points out those areas that need corrective action. It manages the time buffers in a way that they are used to locate and quantify the importance of the disruptions in a plant. Once the main disruptive source has been identified, improvements should be focused on that specific point in order to reduce the amount of protection required in front of the key resources (constraint, assembly or shipping). Reducing protection means reducing WIP, and thus, production lead time.

Schragenheim and Ronen (1991) assert that Buffer Management:

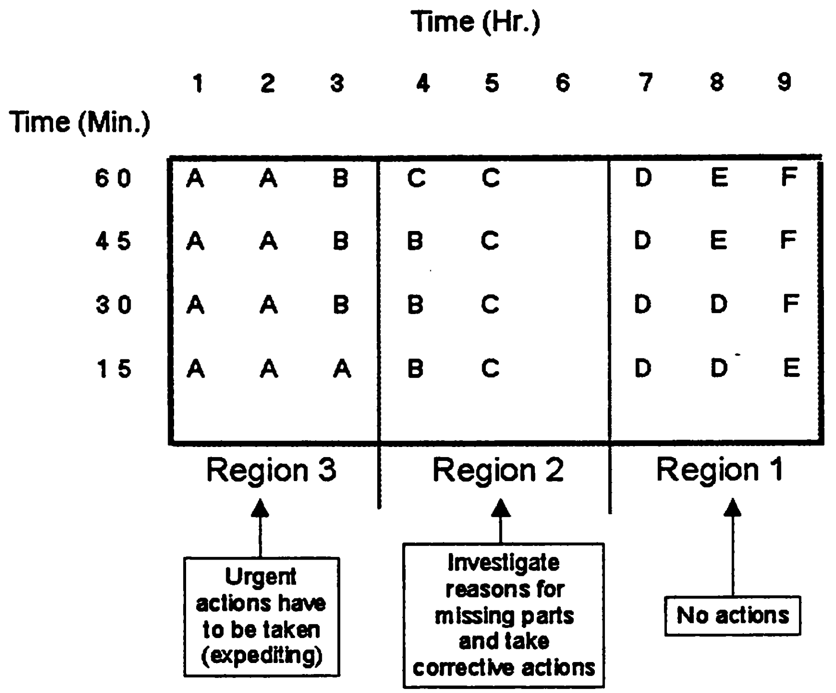
» Serves as an alarm system that spots serious and urgent problems which threaten to disrupt the plan and cause damage to the schedule.

» Provides control of lead time.

» Indicates weak areas, thus prioritizing necessary improvements in the shop floor.

The progression of the orders in the production plan is controlled in BM by simply monitoring the progression of the works at the constraint, assembly and shipping buffers. Tasks monitoring can either be computerized or performed by visual inspection on the shop floor.

As shown in Figure 6.3, BM divides the time buffer into three different regions. Both horizontal and vertical axis represent time. Jobs for the key part (constraint, assembly or shipping) are placed according to the time they are planned to be processed by the constraint. If a job should have reached the constraint but due to the effect of production disturbances has not yet arrived, a "hole" in the buffer is said to exist. Depending on the region where the hole is located, different actions should be taken:




**Figue 6.3**: Buffer Management

- Region 1: any hole in this region, which is in the buffer horizon but still far away from consumption will, be disregarded. There is still enough time until the parts are needed at the key resource.

- Region 2: holes in this middle region warns that the missing parts should be located. They do not yet justify expediting and the reason for the delay should be investigated and corrective actions taken.

- Region 3: the holes identified at this point are very near the scheduled consumption time (which threaten the output of the entire system). This problem becomes a first priority to handle and will probably require expediting.

From the information the buffer holes provide, the location of the missing parts can be determined. This can be done by checking the inventory control records or by simply going and looking. Once the disruptive source has been identified (it will probably be the resource or vendor in front of which the part is waiting), the importance of the disruption should be quantified. Goldratt and Fox (1986) define a disruption factor for each hole in the buffer to be assigned to the source of the disruption. This disruption factor is formed of three parameters:

- "Y": the number of hours the CCR should spend processing the parts. It reflects the magnitude of the damage that will be caused if the material will not arrive at the buffer on time.
- "W": is the protection time that is still left until the absence of the material impacts in the CCR.
- "P": represents the amount of processing time required to complete the parts so they can be processed by the CCR.

This disruption factor can be calculated for each hole in every buffer of the plant, so that by adding the disruption factors for each resource of the plant the main disruption source can be located. The resource or vendor with the highest sum of disruption factors will be the focus of the productivity improvement efforts. The same actions applied to elevate the constraint(s) of the system will then be employed to solve the origin of the disruptions (see section 6.5.1).

<u>+ POOGI</u>

The application of Buffer Management and the aid of the disruption measurements will highlight the point at which to locate the improvement actions. Once the source of disruptions has been removed, protection in front of the critical point can be reduced. This reduction results in (1) reduced time buffers, (2) reduced WIP, and (3) reduced lead times.

However, with the buffer reduction, more holes will be spotted and new disruptions sources identified. New improvement actions will have to be implemented. The Process of Ongoing Improvements (POOGI) is then set, and the company moves towards the goal.

### 6.6.6 - V, A and T plant classification

TOC defines three types of plants as an alternative to the traditional way of classifying the manufacturing systems into project, job shop, batch, line and continuous process (see section 2.2). Plants are categorized into V, A and T according to the specific resource and product interactions that characterize the production process.

Umble (1992) maintains that V-A-T classification "..provides a structure for analysing manufacturing operations which helps managers to understand cause-and-effect relationships and to relate symptoms to the causes of problems". Further, this will enable managers to identify and successfully control the critical aspects of their operations.

V, A and T plants are examined in detail in tables 6.1a and 6.1b (Fawcett and Pearson 1991; Finch 1989; Frizelle 1989; Jacobs 1983; Johnson 1990; Umble and Srikanth 1990; Umble 1992). The more important features of V-A-T plants are:

» V-plant: these plants are characterized by the existence of divergence points in the production process and for producing many end items from a small number of raw materials or component parts. They have a product based layout, with a well defined flow and specialized machinery. V-plants normally have only one constraint that can be identified by looking at the inventory accumulated in front of it.

» A-plant: in these plants a large number of component parts which are assembled into a limited variety of end products (they are thus characterized by the existence of convergent points). Additional characteristics include general purpose machines and the existence of several wandering CCRs for which overtime and expediting are employed. In this case, constraints are identified by looking at the late or missing parts list and constraint and assembly buffers are utilized.

» T-plant: in these plants many parts are processed into a limited number of components that are built to forecast and inventoried for later assembly into custom-ordered final products. Common parts and high inventory levels are the main features of T-plants. The major problem in this environment is the "stealing" of parts waiting for assembly. The number of possible constraints vary from one plant to another; while order histories provide the information required to identify these constraints

» Combination plants: these plants exhibit characteristics of more than one of the above 3 categories. According to Frizelle (1989), V-A-T plant classification is hierarchical in the sense that a plant with both V and A characteristics will show a predominantly A character. Likewise a T plant behaviour will mask both A and V.

| | V-plant | A-plant | T-plant |
|---|---|---|---|
| **CHARACTERISTICS:** | | | |
| 1- <u>Defining aspects</u>: | | | |
| a) Product flow main feature | a) Divergence points | a) Convergence assembly points | a) Divergence assembly points |
| b) Product flow diagram | b) Resembles V letter | b) Resembles A letter | b) Resembles T letter |
| c) Key feature | c) Great number of end items comparing with the number of raw materials. | c) Assembly of large number of unique parts into small number of end items. | c) Small number of parts combined together to form large number of final products. |
| 2- <u>Production aspects</u>: | | | |
| a) Consists of | a) Producers-converters-fabricators | a) Producers-converters-fabricators-assemblers | a) Producers-converters-fabricators-assemblers |
| b) Process | b) Common process, common resources. - few different operations | b) Different processes, different resources - large number of operations | b) Different processes, different resources - No divergent or assembly processes for the components (I-shape) |
| c) Environment | c) Make-to-stock | c) Make-to-order | c) Assemble-to-order |
| d) Production driving force | d) Initial release of material | d) Assembly schedule | d) Final assembly schedule |
| e) Equipment | e) Capital intensive | e) General purpose | e) General purpose |
| f) Flexibility | f) Low | f) High | f) High |
| g) Layout | g) By product (simple) | g) By process (complex) | g) By process (complex) |
| h) Flow | h) Well-defined | h) Poorly defined, chaotic | h) Chaotic (stealing), dissimilar routings |
| i) Lead times | i) Short | i) Long | i) Very long |
| j) Inventories | j) high | j) High | k) Very low |
| k) Stock turns | k) high | k) Low | j) Very high |
| l) Due dates | l) Achieved | l) Missed | l) Missed |
| m) Synchronization | m) Straight forward | m) Difficult | m) Very difficult |
| n) BOM | n) No (I-shape) | n) Yes (A shape) | n) Yes (A shape) |
| o) No. Bottlenecks (CCR). | o) Often only one | o) Several | o) Varies by plant |
| p) Difficulty in finding the CCR(s) | p) Easy to find | p) Difficult: production flow waves create phenomenon of moving bottlenecks | p) Difficult: less precise to find due to the stealing and production flow waves |
| q) ways of identifying the CCR(s) | q) Resource in front of which inventory accumulates. | q) Analysing the late expedite pattern | q) Analysing the late order list |
| r) Placement of buffers | r) CCR(s) and shipping | r) CCR(s), assembly, and shipping | r) CCR(s), assembly, and shipping |
| 3- <u>Production Control</u>: | | | |
| a) Unit of products measure | a) Many (change during the process) | a) Single (discrete products) | a) Single (discrete products) |
| b) Visual parts identification and control | b) Difficult | b) Easy | b) Easy |
| c) Computer controlled system installation | c) Difficult | c) Quite easy | c) Quite easy |
| 4- <u>Other</u>: | | | |
| a) Value adding factor | a) Process hours on expensive capital equipment | a) Labour hour on general purpose machinery | a) -Labour hour in assembly. - Designed the customer required products |
| b) Key issue to address | b) Effective capacity management | b) Components production synchronization | b) Final assembly operation control |

**Table 6.1a**: V-A-T plants general characteristics

| | V-plant | A-plant | T-plant |
|---|---|---|---|
| **TYPICAL PROBLEMS**<br>1- Core problem | 1- Misallocation of material | 1- Misallocation of resources | 1- Misallocation of material at assembly operation ("Stealing") |
| 2- Other problems | 2- Excess inventory (WIP and finished goods)<br>- Inflated production L/T<br>- Shortage of products<br>- High expediting<br>- Overactivation of resources | 2- Wave like flow of work<br>- Low machine utilization<br>- Frequent use of overtime<br>- High inventories<br>- Constant expediting | 2- Large finished good inventories<br>- Unsatisfactory DDP<br>- Long lead times<br>- Constant expediting |
| **PRINCIPAL CAUSE OF PROBLEMS**.................. | * Management actions focused on efficiency and cost:<br>» Large batch sizes<br>» Minimize set ups<br>» Accelerate release of material<br>» Ignore production priorities ("keep busy") | * Management actions focused on efficiency and cost:<br>» Large batch sizes<br>» Accelerate release of material<br>» Reduce No. of setups | * Uncontrolled assembly operation that originates:<br>» Inflated purchased and manufactured products forecasts<br>» Large batch sizes<br>» Minimize setups |
| **CONSEQUENCES**............ | - Large finished goods inventories<br>- Poor customer service<br>- Apparent constant demand change<br>- Marketing complaining of manufacturing<br>- Interdepartmental conflicts | - Assembly complaining of shortages<br>- Excessive unplanned overtime<br>- Unsatisfactory resource utilization<br>- Bottlenecks seem to wander about the plant<br>- Appearance of out of control operations | - Large raw materials, components and finished goods inventories<br>- Poor DDP<br>- Excessive fabrication lead times<br>- Unsatisfactory resource utilization<br>- Fabrication and assembly are treated as separate plants |
| **AIM/OBJECTIVE**............ | 1- Improve customer service<br>2- Reduce production cost | 1- Reduce product cost<br>2- Improve operation control | 1- Improve customer service<br>2- Reduce product cost |
| **CONVENTIONAL SOLUTIONS**.................. | 1- Improve customer service by: increasing finished goods inventories and improving forecasting.<br>2- Reduction of production cost by: reducing direct labour, reducing scrap and improving yield at the processes. | 1- Reduction of unit cost: improving operation efficiency, controlling overtime and achieving automated processes.<br>2- Improving operation control by creating a single integrated production system. | 1- Improve customer service by improving forecasting and inventory planning and control.<br>2- Reducing cost (and price) of the products: improving efficiency operation by reducing setups and overtime. |
| **TOC SOLUTIONS**............ | - Install DBR scheduling technique to primarily reduce Lead Time and then WIP.<br>- Focus engineering and production effort on key activities (in order to improve quality and increase Throughput). | - Apply DBR to synchronize production flow and eliminate the erratic flow.<br>- Focus improvement procedures on the constraints and main sources of variability. | - Eliminate "stealing".<br>- Apply DBR to synchronize production so that inventory and overtime can be reduced.<br>- Focus engineering effort to improve operating efficiency in critical resources. |
| **EXAMPLES** | - Steel industry<br>- Petrochemical plants<br>- Process plants<br>- Chip manufacturing<br>- Textile plant<br>- Paper plant | - Heavy or specialized equipment:<br>» Large generators<br>» jet engine<br>» pumps for aerospace and defence industries<br>» ships | - Household door locks<br>- Small appliance manufacturers (highly optioned families, different packaging variations)<br>- Car plants |

**Table 6.1b**: V-A-T plants general characteristics

### 6.6.7 - The TOC 9 scheduling rules

TOC maintains that overall plant synchronization will be achieved if production flow is governed according to the following scheduling principles (Cohen 1988, Jacobs 1984, Jones and Roberts 1990, Umble and Srikanth 1990):

» Rule 1> *balance flow, not capacity*: many managers in the past have tried to balance all the operations within a plant with each other and with market demand, so that maximum efficiency is achieved. However the existence of statistical fluctuations and dependent events cause that "..no plant could survive if it were truly balanced" (Goldratt 1981).

Therefore, managers have to accept the existence of production disturbances and make the best use of the resources. The ideal manufacturing plant will balance the internal flow by just slightly exceeding the capacity of the resources of the load placed by external demand. This excess capacity will protect the system from changes in market demand.

» Rule 2> *the level of utilization of a non-CCR is not determined by its own potential, but by some other constraints within the system*: as the goal for any business is to increase throughput while simultaneously reducing inventory and operating expenses, the system should be managed in accordance with this goal. CCRs output determine the maximum throughput for the whole plant. Therefore non-CCRs should gear their level of activity to supply the materials needed for the CCR. Any attempt to activate the non-CCRs above the production level dictated by the CCR will increase inventory without affecting throughput.

» Rule 3> *Activation and utilization of a resource are not synonymous:* some managers believe that utilization and activation of a resource are the same, and thus apply local performance measures based on efficiencies. TOC defines utilization as the degree to which the resource should be used in order to pursue the goal; while activation represents the available capacity of the resources. As a consequence of rule 2, resources should be utilized and not activated.

» Rule 4> *an hour lost at a bottleneck is an hour lost for the total system:* CCRs are the link between the manufacturing system and the external demand. When the CCR is a bottleneck, it should not run out of work because that would mean that throughput is lost. At bottlenecks, every available minute is utilized either for production or for setting up the machine for the next part. Non-bottlenecks, on the other hand, contain excess capacity, which means that they have some idle time apart from the time spent in producing and setting up.

» Rule 5> *an hour saved at a non-CCR is just a mirage*: this means that saving time at a non-CCR will only serve to increase the idle time of this resource without affecting throughput. This can lead to better re-evaluate "cost reduction" investments which aim to reduce process times at non-CCRs. However, There are two ramifications that have been overseen by this rule:

1- The actual non-CCR, can be transformed into a CCR if product demand changes (something common in many production environments). As a consequence, actual process improvements that increase non-CCRs available capacity may bring future benefits.

2- Saving time at a non-CCR also permits a reduction in process batch sizes that will impact in the system by speeding up the production flow, reducing inventory and reducing lead time. Thus, *an hour saved at a non-CCR is an opportunity hour* (Cohen 1988).

» Rule 6> *CCRs govern both throughput and inventory in the system:* TOC is based on the efficient management of the constraints of the system, as they are the ones that limit the capacity of the company to achieve the goal.

A bottleneck, by definition, determines the maximum throughput for the plant. Thus, maximising throughput at a bottleneck implies minimising idle time at that resource. TOC advocates the use of long production runs, that result in large process batches and minimal frequency of set ups for these resources.

Furthermore, in order to minimise inventory, non-bottlenecks should process only the level of inventory necessary to keep a constant flow through the bottlenecks.

» Rule 7> *the transfer batch may not (and many times should not) be equal to the process batch:* TOC sets the process and transfer batches with the aim of achieving a smooth process flow and reduce inventory. This is done by dynamically adjusting the sizes of the two types of batches to the specific production circumstances, and by encouraging lot splitting and overlapping. Generally, large process batches will be set at CCRs, and small process batches at non-CCRs. Transfer batches are then defined to limit investment in inventory and operating expenses.

» Rule 8> *the process batch should be variable, not fixed:* this rule challenges the Economic Order Quantity (EOQ) method applied in many companies in the past. EOQ assumes that the transfer and process batches should be equivalent, and derives a batch size based on the balancing of profits (trimmed with the increase of lead times as a result of large batch sizes) and the size of the batches.

TOC suggests that process batches should not be predetermined but constructed dynamically during the scheduling process to answer to specific production situations.

» Rule 9> *schedules should be established by looking at all the constraints simultaneously. Lead times are a result of a schedule and cannot be predetermined:* this last rule contrasts with MRP's scheduling logic of infinite capacity and fixed lead times. TOC addresses real production situations by stressing the importance of constraints and determining production lead times as a result of their schedules, and not the opposite.

### 6.6.8 - The "Drum-Buffer-Rope" scheduling technique

"Drum-Buffer-Rope" (DBR) is the scheduling technique that embraces the above scheduling principles and permits TOC execution at the shop floor level. In essence, DBR (also called "bottleneck/constraint management" technique) synchronizes the manufacturing operations by: (a) linking the output of the constraint resource to market demand, (b) protecting the reliability of customer promises by handling production disturbances through the use of time buffers, and (c) tying the remaining resources to the pace dictated by the constraint resource.

Drum-Buffer-Rope must be considered as a direct application of the first three stages of the "5 focusing steps" decision process:

» Step 1> Identify the system constraint(s)

» Step 2> Decide how to exploit the constraint(s): firstly, the schedule that better fits system available capacity with the market demand is set (Drum). Secondly, the CCR is protected against uncertainty with the use of time buffers (Buffer).

» Step 3> Subordinate everything else to the above decision: the rest of the resources are only activated when their output will help to maintain the CCR busy. This is achieved by releasing material to the plant at the rate dictated by the constraint resource (Rope).

Many authors have focused their attention on studying the DBR scheduling technique (e.g. Cohen 1988; Fogarty and Blackstone 1991; Frizelle 1989; Gardiner et.al. 1993; Goldratt and Cox 1984, Goldratt and Fox 1986, Goldratt 1990b; Jones and Roberts 1990; Schragenheim and Ronen 1990; Srikanth 1987; Umble and Srikanth 1990). The different parts in which DBR is divided in are (see Figure 6.4):

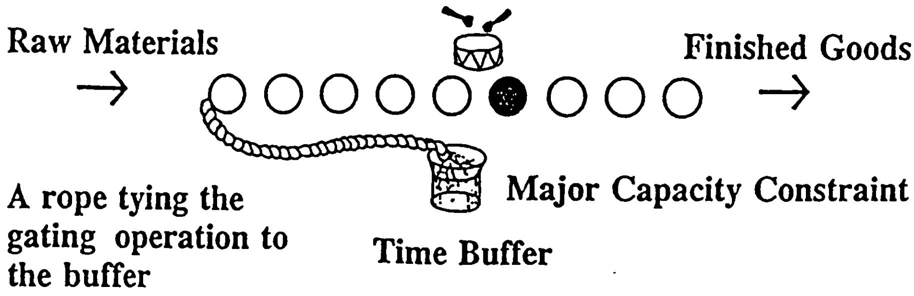



**Figure 6.4**: The Drum-Buffer-Rope scheduling technique (source: Goldratt and Fox - 1986-)

■ The Drum

DBR recognizes that CCRs determine the delivery performance of the whole plant. Therefore, the principal CCR is treated as the "drummer" of the entire system and its schedule represents the "drumbeat" (Drum) of the plant (it dictates the pace at which the rest of the resources should "march"). This schedule is called Master Production Schedule (MPS), and takes into account the modifications to be made to the basic market demand in order to bring the capacity and material requirements of the plan in line with the capabilities of the factory.

If the market is identified as the constraint of the system, a detailed shipping schedule is derived to satisfy demand. In this case, scheduling the shipping is the essence of the exploitation of the constraint, and the detailed shipping schedule becomes the Drum.

On the other hand, if there is a 'clear' CCR in the system, the achievement of the business objectives will be determined by the correct link between the MPS and the customer orders. The problem in this case is that the dates on which customers require their products have little relevance to when the plant can produce them. Therefore, customer due dates, at best, provide a priority sequence, but the only reliable date would be the start day of the schedule. This means that the CCR has to be scheduled forward in a sequence influenced by the order priorities. Orders delivery dates are then defined from the operations sequence; the trick being to match the delivery date as closely as possible to the due date requested.

The selection of the process batch size for the CCR influences greatly in the operations due dates and Drum match. If the size of the process batch is increased, the effective capacity of the CCR is increased by spending more of its time processing and less in set ups. However, it also decreases the flexibility of the system and increases the inventory (and hence the lead time). Reducing the process batch size has the opposite effects. The ability of the system to respond to customer due dates will be determined the proper policy.

Additionally, according to Goldratt and Fox (1986), the following four cases may cause modification to the sequencing decisions taken based on customer due dates:

1- When the lead time from the CCR operation to the completion of the product is greatly different for different products.

2- When one CCR is feeding another CCR. In such a case, by obeying the market due date sequence at the first CCR the second CCR may be starved.

3- Product sequence is changed due to considerations of set-up savings.

4- In cases when a CCR produces more than one part for the same product, the customer due date will not serve as a guidance for choosing the production sequence.

Finally, two other schedules are required at particular points to assure due date performance:

» Assembly schedule: a particular schedule will be required at the assembly operations where constraint parts (i.e. parts processed by the constraint) are assembled to non-constraint parts to ensure that the non-constraint parts are ready to be assembled when the constraint part arrives.

» Shipping schedule for the parts that do not have any operation at the CCR on their route. In this way the achievement of their due date is assured.

■ The Buffer

Production disturbances spreading along the system have the effect of reducing resource available capacity. However, the damage caused by production disturbances will be different at different resources. For example, since CCR outputs influence the performance of the entire plant, these resources should have certain protection against disruptions.

Production disturbances are handled applying time buffers in the following specific parts of the system:

1- In front of the CCR: a buffer is placed in front of the CCR to assure that disruptions in the adjacent resources do not stop this resource. These time buffers are called constraint buffers.

2- In front of assembly points: assembly buffers are placed to ensure that constraint parts do not get stuck at assembly points waiting for non-constraint parts.

3- In front of the last operation: shipping buffers are employed in the cases where the constraint for a product is the market. They are used to protect customer due dates from production disturbances.

■ <u>The Rope</u>

The Rope is the mechanism that synchronizes the manufacturing system by forcing the non-CCRs to work up to the pace dictated by the schedules of the critical parts and no more. This is done by pulling into the plant the materials required at the CCR, assembly and shipping, their respective time buffers before they are required. Therefore, the Rope can be defined as the material release schedule that forces the system to contain only the material required to fulfil the schedules of the critical points.

The rope is calculated backwards by subtracting the time buffers from the Drum, assembly and shipping schedules (the last two are taken into account when they process non-constraint parts). Once material is released to the shop floor, non-CCRs process the parts as soon as they arrive to their position. In this way, parts would reach the critical parts of the system without jeopardizing their schedules (and thus, throughput).

### 6.6.8.1 - OPT and DISASTER scheduling softwares

The Drum-Buffer-Rope scheduling technique can be manually applied without the need for a computer package. However, the need for a software assistance increases with the complexity of the manufacturing system (i.e. amount of data, number of products, number of resources, changes in market demand, rescheduling as a result of production disturbances, etc..). Furthermore, they will be essential to handle cases of several CCRs or when the four schedule complicating conditions occur.

The two scheduling softwares created by Goldratt that apply the DBR technique are:

» OPT: is the software from which the whole TOC management philosophy arouse. Its operational features and success will be reviewed in detail in chapter 9. However, it can be anticipated that it provides what can be considered nearly optimal schedules by utilizing specific management parameters as inputs.

» DISASTER: this package has been recently released to the market. It also embraces the DBR concepts, but unlike OPT, it encourages the scheduler participation in the scheduling process. Different aspects of this software will be evaluated in chapters 10 and 11.

### 6.6.9 - TOC application case studies

There are many reported cases of OPT software implementations and TOC concepts applications. In general, astonishing results are obtained after short installation periods (e.g. large reductions in overall inventory and lead time, improved production control, increased job satisfaction, improved product quality, and improved customer service). However, those benefits are only achieved after a hard re-education process in which traditional production practices are changed for the new TOC concepts.

The case studies related to TOC concepts applications obtained from published papers and personal visits are included in Appendix A.

# 7- EVALUATION OF TOC AS A PRODUCTION MANAGEMENT PHILOSOPHY

## 7.1 - Introduction

In the previous chapter the Theory of Constraints was described as containing two general problem solving approaches and many different production management concepts. This last view of TOC as a production management philosophy will be analyzed in this chapter.

First of all, the TOC concepts will be compared with various production planning and control methodologies and its contribution to the subject highlighted. Then, the way TOC contemplates the general production scheduling principles reviewed in chapter 5 will be examined. Finally, a thorough debate comparing MRP/MRP-II, JIT and TOC's general production management concepts will be performed.

One of the outputs of this analysis is that some authors see TOC as an integration of known concepts (e.g. Ronen and Starr 1990) and other as an enhancement of MRP/MRP-II and JIT (e.g. Jones and Roberts 1990).

## 7.2 - TOC's comparison and contribution to different PPC methodologies

The following sections compare TOC's production management and scheduling concepts with techniques such as Management Science/Operations Research (MS/OR), linear programming, Queuing Theory, Pareto rule, TQM, mathematical programming, JIT, and MRP.

### 7.2.1 - TOC's assumption and goal

» Assumption: TOC assumes that the sum of local optima is not equal to the global optimum (holistic approach).

- This view of the system correlates with JIT's appreciation of it. In addition, according to Ronen and Starr (1990), Management Science/Operations Research (MS/OR) proclaim that a system approach is needed to avoid missing factors that count in the achievement of objectives. Moreover, Burbidge (1985) maintains that "the whole is not the sum of its parts".

- TOC's contribution comes from the definition of the 5 focusing steps and the Thinking Process generic problem approaches by which all type of constraints are identified and exploited in order to achieve global benefits. The above mentioned methodologies lack these system problem solving mechanisms.

» Goal: TOC seeks to achieve the goal of embarking the company in a POOGI by identifying the places where maximum benefits can be obtained from the improvement efforts applied.

- JIT philosophy seeks the achievement of manufacturing excellence by applying a continuous improvement process that focuses on the identification and removal of the constraints of the system. The method employed consists of overall WIP reduction and consequent problem identification and solution.

- TOC with the support of OPT and DISASTER can analyze in advance the impact of alternative approaches without creating problems with their direct installation (like those which may happen with JIT). Furthermore, external constraints are addressed by the TP soft system, while JIT has no mechanism to tackle them.

### 7.2.2 - Production management concepts

» Operational and financial measures: (A) there is a single goal for any business and it is represented in operational and financial terms (T, I, OE, NP, ROI, and CF).

- First of all, authors like Berry (1993), Froeschl (1993), Smith et.al. (1990) and Vollmann (1992) also declare the existence of a production objective to be pursued. Added to this, MS/OR include system objective functions stated in financial and physical production output terms (Ronen and Starr 1990). Finally, the terms of throughput, Net Profit, Cash Flow, and Return of Investment were used long before TOC defined them as performance measures.

- TOC contributes to the subject by (a) understanding and defining I and OE in a broader way, and (b) determining simple local performance measurements to assess the way the undertaken actions affects the goal.

(B) TOC instead of applying the traditional cost accounting local measurements of cost per part and utilization, maintains that "efficiencies" should be avoided because they cause suboptimization (instead T, I, and OE should be employed). Moreover, indirect expenses (e.g. overhead, burden) are allocated according to the use of the constraint; in contrast to the unrealistic way of allocating them according to direct labour hours or floor space utilized in traditional cost accounting

- MS/OR philosophy also claims that measures that avoid suboptimization should be used (Ronen and Starr 1990).

» Production phenomena: TOC declares that all manufacturing systems contain production disturbances and defines the terms statistical fluctuations and dependent events.

- Authors like Berry (1993) and Froeschl (1993), for example, recognize uncertainty as part of the production system. Ronen and Starr (1990) maintains that both s.f and d.e. are a special case of Production and Operations Management approach (P/OM) and are also widely discussed in Queuing Theory. Finally, statistical variations are one of the basic foundations of Deming's management principles (Deming 1986).

- While Deming, JIT and TQM advocate general variability reduction, TOC focuses firstly on reducing CCR variability and then eliminating the fluctuations originated by the "noisiest" non-CCR resource (identified by using the Buffer Management technique).

» V-A-T plant classification: TOC categorises the manufacturing plants according to the type of process flow into V, A, and T plants.

- Many authors have classified the manufacturing plants according to different aspects (see section 2.2).

- TOC (a) utilizes a terminology that is easy to use and enables communication and (b) applies different methods at each plant for the identification of the constraints and assignments of time buffers.

» Buffer Management: this technique is employed to spot the source of production disturbances in order to identify where to focus the improvement efforts.

- BM can be considered an application of the Pareto rule, in the sense that the source of most of problems is identified and tackled first.

- BM contributes by determining the actions to be taken in the different regions where "holes" in the buffers are located, and by defining a disruption factor based on three different variables that identify the major source of disruptions.

### 7.2.3 - Production scheduling concepts

» System constraints: TOC focuses on the efficient exploitation of the constraints of the system in order to obtain global objectives.

- MS/OR maintains that the causal relations between the global objectives and the factors that determine their achievement take into account the existence of constraints (x must be greater or less than y) (Ronen and Starr 1990).

- TOC differentiates between internal and external constraints and apply particular techniques to exploit them. MS/OR on the other hand only contemplates internal constraints.

» 9 scheduling rules

- Rule 1 > "Balance flow, not capacity". The flow balance concept was first applied by JIT in the 1970s by the synchronization of the shop floor operations with the KANBAN technique.

However, TOC, in contrast to JIT, focuses on (a) the exploitation of the constraints of the system, (b) the subordination of the system to them and (c) their protection to achieve overall synchronization. Related to systems protection, TOC uses a reduced amount of inventory located only in front of the critical resources; while JIT locates inventory buffers between each resource.

- Rule 2 > "Bottlenecks determine non-bottlenecks utilization". Linear Programming (LP) includes scarce and non-scarce resources. As non-scarce resources are utilized by the scarce ones, they can be viewed as synonyms of bottlenecks and non-bottlenecks.

TOC defines the role of the CCRs in clear and understandable production terms and stresses their importance in the efficient shop floor management.

- Rule 3 > "Activation is not equal to utilization". LP maintains that the shadow price of a non-scarce resource is always zero.

- Rule 4 > "An hour lost at a bottleneck is an hour lost for the entire system". LP declares that a scarce resource has a positive shadow price. Thus decreasing the amount of this resource will decrease the target function.

- Rule 5 > "An hour saved at a non-bottleneck is a mirage". In LP because a non-scarce resource has a zero shadow price, an hour saved there may be viewed as a mirage.

- Rule 6 > "Bottlenecks govern throughput and inventory". In MRP orders demand acts as a "Drum" and governs throughput and inventory. While in other cases raw material release can act as a "Drum" (e.g. continuous processes).

TOC's contribution is that (a) the constraint is the one that governs the system and acts as a "Drum" and (b) the constraint can be anywhere in the process.

- Rule 7> "Transfer batch should not always equal a process batch". JIT made the same distinction before TOC with the unit process and transfer batch aim.

- Rule 8> "Process batches should be variable not fixed". Mathematical programming techniques determine the size of the batches according to the input variables -that describe the system- introduced.

In TOC, the dynamic determination of the process batches is in accordance with tangible typical shop floor practices and not as a result of complex mathematical algorithms.

- Rule 9> "Set the schedule by examining all the constraints simultaneously". LP exactly contemplates all the constraints simultaneously to avoid suboptimization.

However, as it will be shown in the next chapter, LP lacks all TOC's underlying principles and should only be considered a specific scheduling solution.

» Drum-Buffer-Rope: although DBR will be analyzed in more detail in the next chapter, it can be anticipated that the role the constraints have in determining the maximum capacity attainable by the system is also stated, for example, by Buzacott (1968), Conway et.al. (1988), Dalley and Gershwin (1992), Glassey and Hong (1993), and Lambrecht and Segaert (1990).

Moreover, inventory buffers are also contemplated by JIT and MRP/MRP-II, and authors like Altiok and Stidham 1983; Buzacott 1967, 1971, 1972; Conway et.al. 1988; Dalley and Gershwin 1992; Gershwin and Shick, 1983; Gershwin 1987, 1994; Hillier and Boling 1979; Lambrecht and Segaert 1990; Owen and Mileham 1993 also recognize the utilization of inventory buffers against production disturbances. Finally, Ronen and Starr (1990) declare that MS/OR literature include the Time Buffer concept.

However, these techniques and works by other authors do not address the scheduling problem as a combination of the whole constraint exploitation (Drum), protection (Buffer) and synchronization of the other operations (Rope) concept. Furthermore, they lack, as in the previous case, the underlying TOC management philosophy.

» OPT and DISASTER: these two packages will be studied in the following chapters. However, it can be mentioned that both coincide in the fact that the only data that should be accurate is the one related to the constraints of the system. Therefore, in a way, both softwares apply the Pareto Rule or the 80/20 principle (ABC analysis) to focus on the important data to generate the schedules.

## 7.3 - TOC and the general production scheduling principles

TOC concepts relate to the general production scheduling principles described in chapter 5 in the following manner (see Table 7.1):

» Principle 1: there is no universal scheduling solution.

The 5 focusing steps decision process is defined by TOC as the generic problem solving approach that will enable the company to identify the constraints and locate the improvement actions (POOGI). Moreover, the application of the Thinking Process will permit logically deduce solutions that would "break" the system constraining element. Therefore, according to TOC these two mechanisms can be considered as the tools to be employed to solve the scheduling problem for any production situation. In the next chapter it will be shown how DBR (as implementing the first 3 focusing steps) is more suitable for some production situations than others.

» Principle 2: a feasible schedule cannot contain any conflict between the constraints of the system.

Goldratt (1980, 1990b) asserts that there are two criteria which a schedule has to fulfil in order to be considered as a "good" schedule. The first is that the schedule must be "realistic". Related to this, there are two factors that would make a schedule realistic: the first of the two factors is that the schedule must not contain any conflict between the organization constraints. All internal constraints (i.e. material, capacity and policy) have to be taken into account while creating the schedule.

» Principle 3: system disturbances should be taken into account while developing a schedule.

The second factor that has to be accomplished to declare a schedule as realistic is that it "..must be immunized against a reasonable level of disruptions" (Goldratt - 1990b-). Production disturbances are contemplated in the DBR technique by the introduction of time buffers in front of the critical parts of the system that would protect them from unpredictable disruptions originating at adjacent resources.

» Principle 4: schedules must be evaluated according to the achievement of certain objective/goal.

The second criteria a schedule has to fulfil to be considered as a "good" schedule is that, once this is realistic, it should be in accordance with the goal (Goldratt 1980, 1990b). This means that, it should, first of all, seek to achieve the maximum throughput;

then, reduce the level of inventory; and finally, maintain operating expenses to a minimum.

» Principle 5: there must be a match between the scheduling technique and the production environment.

The production environment is characterized by having: an objective function, some management policies, static elements and dynamic elements.

TOC addresses those four aspects in the following way: (1) The goal represents the objective function; (2) the management policies are clearly and concisely included in the 9 scheduling rules; (3) the static elements of the production systems are partially contemplated in the V-A-T plant classification (in which the typical problems involved at each of them are analyzed); and (4) the dynamic elements are included in the production phenomena definition.

» Principle 6: heuristic approaches will be utilized to solve most of the scheduling problems.

TOC, by applying heuristic-based algorithms in both TOC-based OPT and DISASTER scheduling packages, assumes that analytical approaches are not practical in solving general production problems.

» Principle 7: optimising isolated parts of the system does not necessarily produce an optimum solution for the whole system.

TOC's basic assumption is the result of its holistic vision of the organization. This basic assumption can be stated as: the sum of local optimum is not equal to the global optimum.

As can be seen, TOC correlates with most of the general production scheduling principles. The main difference comes from TOC's recognition of the existence of two general scheduling problem solving approaches which contradicts the general belief in a single universal scheduling solution. However, apart from this difference, the rest of the TOC's concepts totally coincide with the general scheduling principles.

| | | |
|---|---|---|
| GENERAL PROBLEM SOLVING APPROACH | 1- There is no universal scheduling solution. | 1- TOC's 5 focusing steps and Buffer Management provide the generic decision process that will allow to embark the company in a POOGI (DBR is a narrow application of the 5 focusing steps) |
| GENERAL SCHEDULING AIMS | 2- A feasible schedule cannot contain any conflict between the constraints of the system.<br><br>3- System disturbances should be taken into account while developing a schedule:<br>» Modify the system in order to simplify the scheduling problem.<br>» Protect the schedule against unpredictable events.<br><br>4- Schedules must be evaluated according to the achievement of certain objective(s)/goal(s) . | 2- A schedule is considered realistic if:<br>a) Does not contain any conflict between the organization constraint.<br><br>3 b) It is immune to a reasonable level of disruptions.<br><br>4- Once the schedule is realistic, it should try to achieve the goal (i.e. increase throughput while simultaneously reducing inventory and operating expenses) |
| OPERATIONAL SCHEDULING PRINCIPLES | 5- There must be a match between the scheduling technique and the production environment. The following features should be contemplated by the scheduling system:<br>» Management policies and style.<br>» Production objective/goal.<br>» Static elements.<br>» Dynamic elements.<br><br>6- Unless there is a simple scheduling problem -in which case analytical methods can be used-, heuristic approaches will be utilized.<br><br>7- Optimising isolated parts of the system does not necessarily produce an optimum solution for the whole system. | 5- TOC concepts address the scheduling problem in the production environments by applying:<br>» 9 scheduling rules.<br>» The goal: "make money".<br>» V-A-T plant classification.<br>» Production phenomena.<br><br>6- OPT and DISASTER apply heuristic-based algorithms.<br><br>7- TOC's basic assumption state that the sum of local optimums is not equal to global optimum. |

**Table 7.1**: TOC and the general production scheduling principles

## 7.4 - Comparison of TOC with MRP/MRP-II and JIT

The study of the production management philosophies has been the scope of many authors' research work (e.g. Browne et.al. 1988; Fox 1982, 1983; Goldratt and Fox 1986; Goldratt 1990a, 1990b; Henderson and Kenworthy 1990; Jones and Roberts 1990; Luscombe 1992; Orlicky 1975; Patck 1991; Shingo 1989; Villa and Watanabe 1993; Wu 1992). In this section aspects like (a) PPC, (b) the way production disturbances are handled, (c) production scheduling operational principles, and (d) applicability will be reviewed in each production philosophy.

### 7.4.1 - General review

The following aspects concerning the three production management philosophies can be highlighted:

» A matter of culture: according to Shivnan et.al. (1987) western thinking is dominated by the Scientific Approach that is characterized for being analytic and quantitative. This leads to the belief that the whole can be reduced to its parts and each examined on its own and once all parts are understood, the system is assumed understood. This thinking is clearly reflected in MRP/MRP-II. MRP/MRP-II attempts to integrate the whole organization by using a centralized computer system, but still it lacks a systems perspective when it tries to achieve global objectives from local ones.

In contrast, easter thinking is system oriented and believes that the whole is greater than the sum of its parts. This systems approach orientation can be seen in JIT, in the sense that tries to encompass all plant activities towards the final objective of producing what is needed, when is needed and how is needed.

Finally, TOC has many similarities with MRP/MRP-II from a structural point of view (centralized computer system trying to manage the whole plant) and with JIT from a philosophical point of view (all the underlying principles and the assumption that local optimums do not produce a global optimum). TOC can be seen as an attempt to bridge the gap between western and eastern thinking.

» Workforce involvement: there is also another marked cultural environment difference between western and easter when dealing about the workforce involvement. While in the east, operators are directly involved in production management and improvement campaigns; in the west, there is apathy in the workforce towards the company. The average worker in the West will not be interested in anything which may make his/her job more complex or introduce further responsibilities (although this attitude seems to be -fortunately- slowly changing).

Both behaviours are clearly reflected in the production management philosophies:

- JIT contemplates workforce participation as a basic aspect.
- MRP/MRP-II leaves shop floor management and control in the hands of the foremen. Operators participation is not taken into account.
- TOC creates schedules for the CCRs that have to be strictly followed in the shop floor in order to attain the goal. Foremen and operators should adhere to the schedules (Drum and Rope).

» Scope of the three philosophies: Browne et.al. (1988) argue that MRP/MRP-II (being a computerized approach that breaks customer requirements into time-phased purchased and manufactured products) is only concerned with the logistics of "when".

JIT takes a larger view and is concerned with "what" the product is, "how" the product is manufactured and the logistics of delivering it on time to the customer.

TOC, understood as a management approach focused on production scheduling and control, is (like MRP/MRP-II) mainly concerned with the logistics of "when" and "how many". However, TOC (similar to JIT) also seeks to influence "how" the product is manufactured, through modified process and transfer batches, emphasising in increasing the capacity of the CCRs, removing the source of production disturbances, etc..

» Continuous improvement of manufacturing operations: both JIT and TOC seek the synchronization of production operations by reducing the inventory levels tied in the system. JIT attempts to improve the production process by reducing resource variability and overall inventory indistinctly in all phases of the system.

TOC, on the other hand, seeks to "elevate" the constraint of the system, while simultaneously attempting to remove the major source of disruptions (identified applying BM). TOC has a clearer vision than JIT of where to locate improvement efforts in order to enhance the whole system. Furthermore, OPT and DISASTER provide TOC with the simulation tools by which the results of improvement actions can be anticipated.

MRP/MRP-II lacks the Production Activity Control (PAC) capability and puts little effort in improving the manufacturing process.

» Installation period: the application of any of the three philosophies requires long installation periods:

- MRP requires a massive data input and continual daily information loading. Additionally, planners have to get use to the operational features of the system.

- JIT's basic initial requirement is the radical cultural change it involves. Operators, foremen and managers have to be re-educated to work in a just-in-time fashion.

- TOC, like JIT, requires a radical cultural change. Traditional practices have to be replaced with new methods and techniques (e.g. operational and financial measures, DBR, local performance measures, BM, etc..). Furthermore, OPT and DISASTER require similar data to MRP, and software users have also to get use to its features.

» Off-line vs on-line systems: on-line systems are capable of answering in real time to changes in the dynamic elements of the system (e.g. machine breakdowns, longer than usual set-ups, tool-failures, demand change, etc..). Off-line systems cannot respond to disruptions as they occur.

JIT can be seen as an on-line system; while MRP/MRP-II and TOC (with the manual or computerized application of DBR) are off-line systems.

Finally, a summary of the different attributes of the production philosophies is shown in Tables 7.2a and 7.2b.

### 7.4.2 - PPC in the production management philosophies

+ Centralized vs decentralized control

Both MRP/MRP-II and TOC are characterized by a centralized control structure. However, as MRP/MRP-II comprises many management functions apart from manufacturing (engineering, purchasing, finance, etc..) it has to be organizationwide focused. On the other hand, TOC can be applied in a decentralized manner to schedule a plant, a family of products, or simply a manufacturing cell.

JIT on the other hand, is a result of a systems approach that, due to many interrelationships within the subsystems of manufacturing, enables the creation of autonomous focused factories or manufacturing cells. Such autonomy and division into subsystems characterises a decentralized control structure that entails defining individual goals and allows the subsystems certain freedom to plan and control so as to achieve these goals.

| | MRP/MRP-II | JIT | TOC |
|---|---|---|---|
| DEFINITION.............. | - Centralized production system to plan production. | - Overall philosophy that seeks to eliminate waste and achieve production excellence. | - Management philosophy based on the efficient exploitation of the system constraints. |
| TECHNIQUE............... | - Break orders into time-phased purchased and manufactured requirements. | - Synchronization of all production activities through minimum inventory. | - Recognize CCRs and discriminate them from other resources in order to achieve a fast and smooth production flow (5 focusing steps and 9 scheduling rules). |
| GOAL....................... | - Release orders "what" and "when" are needed. | - Product design and engineering excellence (zero "everything")<br>- Reduce lead times | - "To make money now as well as in the future".<br>- Establish a POOGI. |
| ENVIRONMENT....... | - Unpredictable demand.<br>- Process oriented layout (complex).<br>- Great variety of products.<br>- Unpredictable process times.<br>- Multi-level batch production industries. | - Predictable demand.<br>- Flow-based production (product oriented layout). (GT, manufacturing cells).<br>- Low variety of products.<br>- Reliable machines with low internal fluctuations.<br>- Line production situation<br>- High volume production. | - Unpredictable demand.<br>- Process oriented layout.<br>- High or low products variety.<br>- Predictable process times (vital for finite scheduling).<br>- Fairly stable production situation to effectively exploit bottlenecks.<br>- Batch and line production situations. |
| CHARACTERISTICS: | Make to stock | Make to order | Make to stock/order |
| * Scheduling........ | - Infinite capacity scheduling.<br>- Backward scheduling.<br>- Computerized approach.<br>- Transfer and process batches are equal.<br>- Lot splitting and overlapping are not allowed.<br>- Safety stocks and slack time employed to handle production disturbances.<br>- Medium/long forecasted MPS.<br>- Fixed, average lead times.<br>- Slow scheduling process. | - Finite capacity scheduling (KANBAN).<br>- Line balancing and backward scheduling with Kanban.<br>- Visual/manual scheduling.<br>- Transfer and process batches are not assumed equal.<br>- Process batches should be as small as possible.<br>- Excess capacity and flexibility are used against uncertainty.<br>- Local scheduling decision.<br>- Schedule stability needed.<br>- Operators in charge of scheduling decisions. | - Finite capacity is assumed (determined by the CCR)<br>- Forward CCR schedule and rest of the resources subordination to it (DBR)<br>- Manual or computerized scheduling.<br>- Transfer and process batches are not equal.<br>- Batch splitting and overlapping are allowed.<br>- Production disturbances are handled with the introduction of time buffers in front of critical parts of the system.<br>- Predictable process times indispensable to avoid continual rescheduling.<br>- Fast scheduling process.<br>- 9 scheduling rules.<br>- OPT and DISASTER. |

| | MRP/MRP-II | JIT | TOC |
|---|---|---|---|
| * Process control..... | - Order release control is the basis for the overall flow control (Push logic). | - KANBAN technique (pull logic). | - Bottleneck management (pull logic -Rope-). |
| * Other.............. | - MPS drives MRP.<br>- Centralized system.<br>- All resources equally treated.<br>- Management to stock.<br>- Traditional cost accounting applied. | - Decentralized system.<br>- Families of products.<br>- Management by sight.<br>- Multiskilled operators.<br>- Large underlying philosophy (system redesign). | - Bottlenecks/non-bottlenecks.<br>- Bottlenecks vs CCRs.<br>- Particular operational and financial measures.<br>- Local performance measures<br>- Centralized system.<br>- V-A-T plants.<br>- Production phenomena. |
| ADVANTAGES........... | - Hierarchical planning useful at complex and non-repetitive manufacturing systems.<br>- Sharing information overall integration could be achieved.<br>- Planned lead times useful at a tactical management level.<br>- Simulation capabilities. | - Business perspective (customer-factory-suppliers).<br>- Workforce participation.<br>- Continual lead times and batches reduction.<br>- Easy control through extensive plant design.<br>- Smooth production flow that leads to: reduced inventory and short lead times. | - Overall production management philosophy applying "original" methods (DBR, T, I, OE, 9 rules, BM, bottlenecks).<br>- Seek for the POOGI.<br>- Special attention given to production disturbances.<br>- Easy to understand terms.<br>- Still growing philosophy.<br>- Low inventories and short lead times achieved through flow synchronization. |
| DISADVANTAGES..... | - Great amount of accurate data gathering and maintenance.<br>- Fixed lead times to schedule production.<br>- Inadequate PAC facilities.<br>- Unfeasible schedules.<br>- Unrealistic lot sizing method.<br>- long scheduling process.<br>- High investment in inventories.<br>- Realistic MPS needed.<br>- Long installation period (need of training). | - Appropriate production environment required.<br>- Many conditions needed to apply Kanban.<br>- Certain excess capacity needed.<br>- Indispensable high machine reliability.<br>- Suppliers must work with JIT.<br>- Radical mentality change.<br>- Continual workforce training.<br>- Expensive installation. | - Tight finite schedule.<br>- Need of great amount of very accurate data.<br>- Predictable process times required.<br>- Lack of workforce involvement.<br>- Radical mentality change (need of education).<br>- Narrow scope of V-A-T. - Is TOC a "money making machine"?. |

**Tables 7.2a and 7.2b**: general comparison of the production management philosophies

+ Push vs pull logic / Just-in-case vs just-in-time

In the pull system applied in JIT and TOC, the release of materials into the plant results from the chain reaction initiated when the market (JIT) or the CCR (TOC) pulls them into the system. This pull mechanism is also called just-in-time (Goldratt and Fox 1986, Wu 1992) and limit the inventory held in the system to the length of the ropes (predetermined inventory buffers).

On the contrary, the push or just-in-case system employed in MRP/MRP-II, does not make any capacity considerations and material is normally released to the plant according to the level of capacity of the first operation ("keep busy" traditional management fashion). Then, the orders are pushed along the production process once the operation is completed and the succeeding resource is idle. The result is a considerably higher inventory than in the pull system.

The comparison of the PPC functions at the three philosophies is shown in Table 7.3.

| FUNCTIONS | MRP/MRP-II | JIT | TOC |
|---|---|---|---|
| Strategic decisions | - Production Planning | - Long Term Production Plan | - Long Term Planning |
| Final product demand | - MPS | - MPS (Monthly Production Plan) | - MPS |
| Initial capacity analysis | - RCCP | - MPS (Monthly Production Plan) | - MPS |
| Materials required | - MRP | - Detailed Schedule/ Assembly Sequence | - MRP |
| Detailed capacity analysis | - CRP | - Detailed Schedule/ Assembly Sequence | - CCRs schedule |
| Production schedule | - PAC | - Kanban | - CCRs schedule |
| Production control | - PAC | - Kanban | - BM |

**Table 7.3**: PPC in the production management philosophies

### 7.4.3 - Production disturbances

Production disturbances play a key role in the efficient scheduling and control of the manufacturing operations. In section 6.6.4 it was pointed out how the combined effect of statistical fluctuations and dependent events disrupt the normal production flow, and, if not properly handled, will increase WIP and lead times, and reduce throughput.

#### 7.4.3.1 - Handling production disturbances

There are two general ways of reducing the negative effect of production disturbances:

1 - Reducing the amount of disruptions: the degree of the disruptive factors can be diminished by:

(a) Increasing resource efficiency by reducing the frequency of unpredictable events such as machine breakdowns or tool failures. This is achieved by a good engineering and operations management (e.g. improving the reliability of the machine components, optimizing the tool life, and managing efficiently the maintenance operations).

(b) Reducing the fluctuations degree. The magnitude of the internal variability that affect process and set up times can also be lessened by focusing on engineering aspects (e.g. standardizing tool changers, reducing the "noise" of surrounding machines causing the resource to undergo continual adjustment, improving the quality of the tools, etc..).

2 - Protecting the system against production disturbances: Buzacott and Shanthicumar (1993) maintain that there are three ways of reducing the impact of production disturbances:

(a) Employing redundant stations: so that in the form of standby stations they can share the production load when one of them breaks down.

(b) Utilizing cross paths: this solution is even more expensive. Cross paths are a special case of redundancy in which entire sections of parallel machines act as a backup to one another. Thus, when a station or group of stations breakdown, a cross path connecting their parallel machines would allow the system operate.

(c) Utilizing intermediate inventory buffers: these buffers stop the spread of production disturbances by "breaking" resource dependency (i.e. a resource can continue working even if all the upstream resources are down). The buffer capacity -size- to locate between two resources will be influenced by (1) the cost of the WIP in the buffer, (2) the level of disruptions in previous resources, (3) the inherent capacity at the preceding resources, and (4) the inherent capacity at the current resource.

The utilization of inventory buffers is considerably cheaper than the previous two solutions. However, in process inventory inevitably result in tied up capital material, increased production costs (e.g. cost of the space it occupies and handling cost), increased production lead times, affects products quality (parts are vulnerable to damage), and hide the causes of disruptions.

#### 7.4.3.2 - Handling production disturbances in MRP/MRP-II, JIT and TOC

The three production philosophies -direct or indirectly- recognize the existence of production disturbances and apply different measures to handle them (see Table 7.4):

1- MRP/MRP-II > eliminate production dependency: MRP/MRP-II inflates component lead times by including a large slack time against uncertainty (queue times represent 80% of the total lead time -Browne et.al. 1988-). Then, when MRP/MRP-II schedules backwards from the final product due dates, the component lead times give rise to large inventory buffers between the resources. Additionally, MRP/MRP-II permits the location of particular safety stocks anywhere in the system. As a result, production disturbances are tackled by breaking resource dependency with the introduction of inventory in the system.

2- JIT > eliminate the fluctuations: JIT, in contrast to MRP/MRP-II, tries to eliminate resource variability (as does TQM) by applying the following continuous improvement procedure: (1) reduce the batch sizes in order to reduce WIP and identify the major source of disruptions; (2) apply engineering effort and preventive maintenance to reduce the fluctuations; (3) once the problem has been solved, batch sizes are reduced again and the new source of disruptions identified.

In this way, JIT seeks the achievement of the "zero inventory" goal. However, to maintain the same throughput while operating without WIP production flow must be totally synchronized and production disturbances must not exist. As total synchronization and total elimination of process variability is impossible to achieve. JIT -through the Kanban technique- locates small inventory buffers between the resources. However, these buffers are so small that if there is a stoppage at any operation, all the resources and assembly operations will come to a halt almost immediately (Fox 1982). Finally, JIT also tackles production disturbances by utilizing very reliable and flexible equipment, and multiskilled operators.

3- TOC > deals effectively with statistical fluctuations and dependent events: TOC recognizes the existence of production disturbances (production phenomena) and even goes one step further claiming that due to them, no plant can be truly balanced and a CCR must exit (Goldratt 1981, Johnson 1990). TOC applies the DBR scheduling technique to exploit the constraints of the system and at the same time protects the critical parts of the plant from the negative effects of production disturbances. The way in which DBR handles production disturbances is:

(a) Drum: the CCR of the system is identified and the schedule that would bring maximum throughput through the exploitation of the CCR is created. Moreover, engineering effort is employed to increase CCR capacity (elevate the constraint).

(b) Buffer: time buffers are located in front of the critical parts of the plant (i.e. constraint, assembly, and shipping) to protect system throughput from the effects of production disturbances. TOC does not attempt to achieve "zero inventory", rather it stresses the role of inventory as throughput protector, and seeks to locate the appropriate amount of it in the appropriate place and at the adequate moment (time buffer). Further, it relies on non-constraints excess capacity to "catch up" production when production disturbances jeopardize the schedule.

Conway et.al. (1988) maintain that buffer stocks provide protection against disturbances and increase system efficiency. So, it is hard to understand how "zero inventory" could be considered an ideal situation (JIT). They argue that complete buffer removal is unattainable and counterproductive, and that it is not always true that the less WIP in the system, the better it operates. Goldratt (1990a) declares that "..zero-inventory is synonymous with zero-production and thus zero-Throughput. Not having inventory buffers is equivalent to declaring that Murphy does not exist". Further, he claims that as long as the system contains both statistical fluctuations and dependent resources, there is a tradeoff between inventory and current throughput.

Finally, Goldratt (1990b) also maintains that both MRP/MRP-II and JIT, by placing inventory between the resources of the system, "..have allowed more time to be spent for immunization than for actually carrying out the tasks themselves....both methods have tried to immunize the schedule itself rather than the result of the schedule".

(c) Rope: is the logical link between the CCR and the gating operations. Material is released to the plant at the pace dictated by the CCR in order to: (1) subordinate the rest of the resources to the CCR, and (2) maintain WIP to a minimum.

TOC, like JIT, also tries to eliminate the major source of disruptions in the system and at the same time reduce WIP employing the Buffer Management method. However, TOC unlike JIT, has the support of OPT and DISASTER to assess the impact of batch reductions or engineering solutions ("What if?"/simulation possibility), being able to anticipate their results without suffering the effect of erroneous resolutions.

| | SOLUTION | TECHNIQUE |
|---|---|---|
| MRP/MRP-II | » Eliminate production dependency | » Inflate component lead times that will introduce large inventory buffers at all the stages of the production process |
| JIT | » Eliminate the fluctuations | » (1) Reduce overall inventory by reducing the batch sizes. (2) Identify and solve the source of disruptions. » Locate small inventory buffers between all the resources of the system (Kanban) |
| TOC | » deal effectively with statistical fluctuations and dependent events | » Drum-Buffer-Rope (OPT and DISASTER) » Buffer Management |

**Table 7.4**: production disturbances in the management philosophies

### 7.4.4 - Production scheduling

+ Role of constraints

The function production constraints have in the three philosophies is significantly different:

- The role constraints play in TOC has been extensively remarked. Constraints are identified for each new production demand and they determine throughput and inventory in the system.

- In MRP/MRP-II, the market is the system external constraint and the orders (tracked in a push manner) serve as the Drum.

- In JIT, the final assembly sequence generated from daily external demand pulls material from previous processes with the aid of the Kanban technique. All resources are equally treated and they are only activated when their output is required in subsequent operations.

+ Scheduling approaches in the production management philosophies

The scheduling approaches (reviewed in chapter 4) employed in the production philosophies are:

- MRP/MRP-II generates production orders based on fixed components completion lead times. Once available capacity is checked (CRP), the orders are prioritized by the PAC module according to particular dispatching rules. The heuristic rules normally applied are based on customer due dates and production is sequenced in a First-in-First-out basis.

- OPT and DISASTER scheduling rules will be analyzed in following chapters. However, it can be anticipated that they also produce CCRs schedules based on customer due dates but applying more complicate heuristic rules than those of MRP/MRP-II.

- JIT utilizes production levelling and line balancing techniques at the planning level to guarantee a smooth production flow in the shop floor level. At this level, neither analytical nor heuristic approaches are used to schedule the orders. On the contrary, the manual Kanban technique guarantees the assembly schedule completion.

### 7.4.4.1 - Operational scheduling principles in the production philosophies

In this section, the scheduling principles applied at the shop floor level by the three management philosophies are reviewed and compared (see Table 7.5).

**Principle - 1:**

**MRP/MRP-II** -> Balance capacity, then try to maintain flow.

**JIT, TOC** -> Balance flow, not capacity.

MRP/MRP-II tries to balance the capacity of the resources with the market demand in order to ensure high utilization factors. Then, using the "push" logic it attempts to create a continuous flow of materials.

JIT and TOC argue against balancing capacity and seek a flow balance through the plant. JIT was the first one to adopt this principle by the utilization of the manual Kanban technique. TOC on the other hand, instead of applying physical pull methods (Kanban), uses the "Rope" concept to control the release of raw materials into the system.

**Principle - 2:**

**MRP/MRP-II ->** Capacity and priority are considered sequentially. Process lead times are not dependent of the schedule (they are fixed and known a priori).

**JIT, TOC ->** Priority and capacity are considered simultaneously. Process lead times depend on the schedule (they are not fixed and known a priori).

In MRP/MRP-II priorities are assigned to jobs according to fixed lead times, and those jobs with higher priority are processed first. Then the feasibility of the schedule is checked by the Capacity Requirements Planning (CRP) module. If resource capacity problems appear, production priorities are revised. This procedure is repeated again and again until the schedule is considered feasible.

JIT advocates a complete redesign of the production system in order to answer to daily demands in a real time, finite capacity basis.

TOC on the other hand, creates a tight schedule for the CCRs by setting all of them simultaneously (to avoid suboptimization), and by contrasting priorities and capacity at the same time. Lead times are not considered known a priori, but depend on the sequencing at the limited capacity resources. Exact lead times and priorities cannot be determined unless capacity is considered.

**Principle - 3:**

**MRP/MRP-II, JIT ->** There are not distinctions between resources while creating the schedule.

**TOC ->** We should focus on the constraint resource(s) because it govern(s) throughput and inventory in the system.

While assigning job orders to the available resources, MRP/MRP-II treats all of them equally. Hence, jobs are assigned assuming infinite resource capacity. MRP/MRP-II production philosophy operates in such a way that (Ronen and Starr, 1990) "orders govern inventory and throughput in the system". Controlling the fulfilment of the orders, the whole system is under control.

TOC maintains that a scarce resource is the resource that governs the whole system and thus its output.

JIT seeks a total plant synchronization, and does not make any difference between the resources when the real time requirements are pulled from succeeding operations. The main drawback of this strict synchronization is that when one resource stops all the downstream resources "fed" by it have to stop as well.

**Principle-4**

**MRP/MRP-II ->** Resource utilization and activation are the same. Resource capacity should be fully utilized.

**JIT, TOC ->** Resource activation is not the same as resource utilization. Full resource capacity utilization result in excess inventory.

As cost accounting traditional measures are employed in MRP/MRP-II, resource efficiency is encouraged, and resource utilization and activation become synonymous.

In contrast, JIT methodology spreads the message of: "produce only what is needed and when is needed". Resources are only activated when the downstream resource require a component of them, otherwise they stay idle. JIT suggests that full resource utilization only leads to: total inventory increase, difficult control, long lead times, and production "waves" (uneven -non-smooth- production flow). Related to this, TOC philosophy claims that the only resource that should be fully utilized is the systems bottleneck. Non-bottlenecks must be activated only when their output serve to maintain the bottleneck busy (or results directly in throughput when there are no bottlenecks in the route).

**Principle - 5:**

**MRP/MRP-II ->** The way to reach a global optimum is by ensuring local optimums.

**JIT ->** Reorganizing the system into focused factories or manufacturing cells that are synchronized to each other, local goals are in accordance with global goals.

**TOC ->** The sum of local optima do not add up to the optimum of the whole.

MRP/MRP-II encourages local resource and operator efficiency and seeks to obtain a global optimum by ensuring local optimums.

JIT must be considered as a holistic approach that focuses special attention on achieving whole plant synchronization through designing autonomous subsystems. These subsystems are interconnected to each other so that local optimums lead to global optimums.

TOC is another example of holistic approach. However, unlike JIT, it tries to achieve an effective management of the shop floor by focusing on the constraint resources and by subordinating the rest of the system to them.

**Principle - 6:**

**MRP/MRP-II, JIT, TOC ->** <u>The system is characterized by containing production disturbances.</u>

This is the only principle where the three management philosophies coincide. MRP/MRP-II and JIT do not recognize explicitly the existence of production disturbances; however, they apply particular measures to handle them (reviewed in section 7.4.3). TOC on the other hand, is the only philosophy that recognizes their existence (it calls them production phenomena) and contemplates them in the DBR scheduling technique.

| | MRP/MRP-II | JIT | OPT/TOC |
|---|---|---|---|
| OPERATIONAL SCHEDULING PRINCIPLES | 1- Balance plant capacity, then try to maintain flow.<br>2- Capacity and priority are considered sequentially. Process lead times are not dependent of the schedule (they are fixed and known a priori)<br>3- All resources must be equally treated while creating the schedule.<br>4- Resource utilization and activation are the same. Resource capacity should be fully utilized.<br>5- The way to reach a global optimum is by ensuring local optimums.<br>6- Production uncertainties exist in the system. | 1- Balance flow, not capacity .<br>2- Flow and capacity are considered simultaneously. Process lead times depend on the schedule.<br>3- There is no distinction between resources while creating the schedule.<br>4- Resource activation is not the same as resource utilization. Full utilization of resource capacity result in excess inventory.<br>5- Reorganizing the system into focused factories or manufacturing cells that are synchronized to each other, local goals are in accordance with global goals<br>6- There are disturbances in the system. | 1- Balance flow, not capacity.<br>2- Priority and capacity are considered simultaneously.Process lead times depend on the schedule (they are not fixed and known a priori).<br>3- We should focus on the constraint resource(s), because they govern throughput and inventory in the system.<br>4- Utilization and activation of a resource are not synonymous. Non-constraint resources must be activated only when their output will keep the constraint constantly busy.<br>5- The sum of local optima do not add up to the optimum of the whole.<br>6- All systems are characterized by the existence of dependent events and statistical fluctuations. |

**Table 7.5**: operational scheduling principles in the management philosophies

### 7.4.5 - Production management philosophies applicability

+ Adequate production environments

The three philosophies have inherent characteristics that fit better with some particular production environments than others:

- JIT requires the following conditions to be successfully installed (Browne et.al. 1988, Fox 1983, Goldratt 1990b, Wu 1992): high volume production, repetitive manufacturing situation, low variety of products, accurately predictable demand, multiskilled-operators and reliable and flexible resources. Without these attributes, some of the JIT methodologies may yield useful process improvements, but the whole JIT philosophy implementation would be impossible.

For companies operating in non-repetitive production environments, there is a question of selecting either MRP/MRP-II or TOC.

- TOC's production management concepts will be more suitable for make-to-stock or make-to-order situations characterized of containing great variety of products, high volume production and fairly stable demand (in order to have stable constraints)(Frizelle 1989, Jones and Roberts 1990, Shivnan et.al. 1987). In addition, the TOC-based software finite capacity consideration will better fit in the cases where the process is predictable in its behaviour or is machine dominated.

- Finally, MRP/MRP-II is better suited to make-to-stock cases that contain high volume production, great variety of products, and unpredictable demand (Browne et.al. 1988, Fox 1983). Moreover, fixed, average lead times and the provision of "What if?" tools at the planning level will be beneficial in unpredictable production processes or very people-intensive situations.

Figure 7.1 shows the management philosophies location in terms of products and manufacturing complexity.

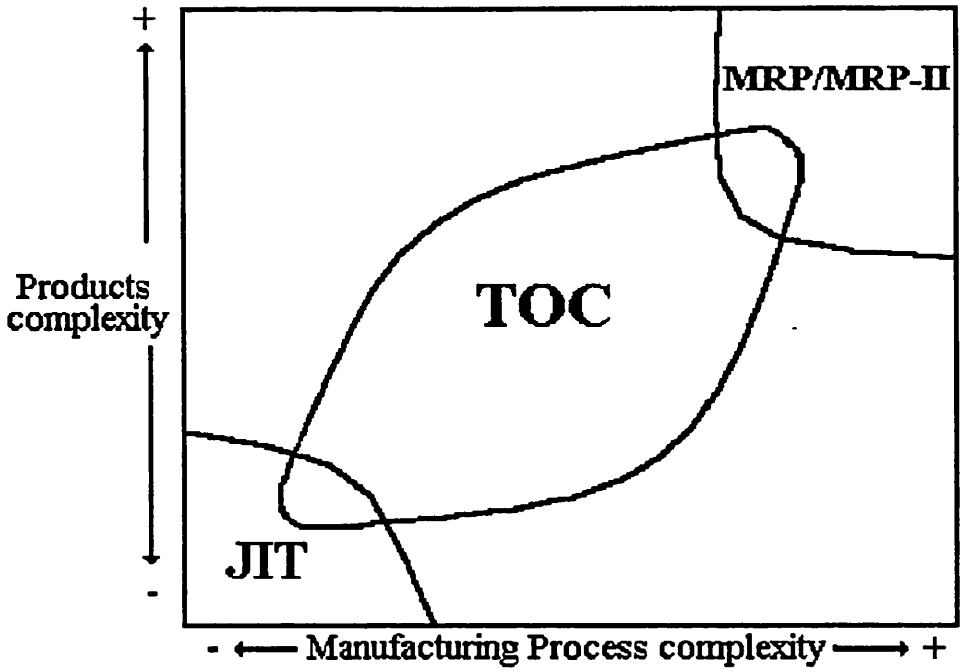



**Figure 7.1**: adequate manufacturing environments for the production philosophies (source: Jones and Roberts -1990-).

+ Manufacturing systems

As a result of the above production environment suitability, the production management philosophies will be better applied in the manufacturing systems comprised in Table 7.6.

| | **MRP/MRP-II** | **JIT** | **TOC** |
|---|---|---|---|
| **Suitable**............. | Batch, (Line > MRP module) | Line (FMS, GT) | Batch, Line |
| **Possible** -but not very practical-....... | Jobbing | Continuous process | Continuous process |
| **Unsuitable**.......... | Project, Continuous process | Project, Jobbing, Batch | Project, jobbing |

**Table 7.6**: link between the production philosophies and the manufacturing systems

### 7.4.5 - Combination as a solution?

In most cases, none of the philosophies will perfectly fit with the factory requirements, and a so called "hybrid architecture" or combination of methodologies may be the appropriate solution. In recent years some authors have followed this way of thinking (e.g. Browne et.al. 1988; Jones and Roberts 1990; Ptack 1991; Villa and Watanabe 1993) and many companies have successfully adopted this solution (e.g. GM in Windsor -Ontario- and AT&T in Reading, USA -see Appendix A-). One of the many possible combinations of the production philosophies is proposed by Browne et.al. (1988)(see Figure 7.2):

» Strategic issues: JIT has a lot to offer at this level because it seeks to "mould" the production environment to the demanded products. It supports the strategic layer by trying to match the product design and the production process with the market demand.

In terms of capacity analysis, JIT levelling techniques will be appropriate in repetitive environments. In the other cases, depending on the process predictability, MRP/MRP-II resource capacity verification or TOC's finite capacity analysis will be better tools.

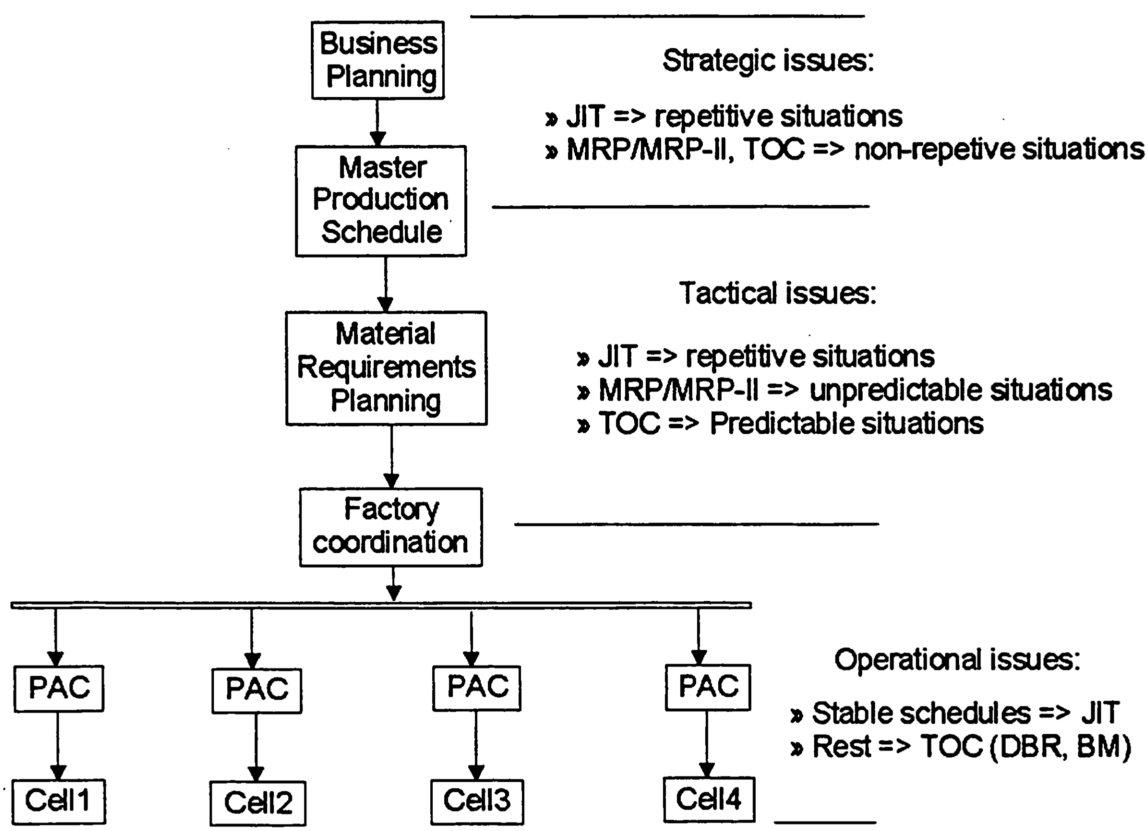



**Figure 7.2**: combination of production management philosophies (source: Browne et.al. -1988-)

» Tactical issues: these are related to the generation of detailed plans to meet the demands imposed by the MPS. In repetitive manufacturing situations where JIT can be applied, tactical planning can be easily achieved using production smoothing and monthly and daily loads adaptation.

MRP/MRP-II's use of planned lead times is adequate in the context of complex and unpredictable manufacturing systems. But planned lead times should be interpreted as a guide for operational control purposes and not as a detailed shop floor schedule.

On the other hand, TOC-based software can be used for more detailed capacity analysis and CCR's identification.

» Operational issues: the execution of the planned production takes place at this level. In cases where the plant layout is formed by product based manufacturing cells and the schedules are very stable, the Kanban decentralised control system can be installed. In other cases, TOC's DBR and BM techniques will have a lot to offer at this operational level.

### 7.5 - Conclusion

The following strong and weak points of TOC can be drawn as a conclusion.

+ Strong points of TOC

» Overall production management philosophy: TOC was born as a scheduling computer software. It then evolved and created the mechanisms to manage efficiently the manufacturing operations (e.g. DBR, 9 scheduling rules, BM, operational and financial measures, performance measures, bottlenecks vs CCRs, etc..). Finally, TOC with the 5 focusing steps and the recent development of the TP has extended its concepts to the whole organization.

» Seek for the POOGI: TOC clearly states that the objective of any business is to embark in a Process of Ongoing Improvement. It warns of the risk of letting inertia being the constraint that would make the company remain with traditional methods and not grow to be able compete in the actual highly competitive market. It provides the 5 focusing steps, BM and TP as the tools that would embark the company in the POOGI.

» The role of production disturbances is stressed: with the recognition of the production phenomena (statistical fluctuations and dependent events) the fundamental role production disturbances play in production scheduling is stressed. Unpredictable events and variability are the basic dynamic aspects contained in all manufacturing systems that must be taken into account while developing any detailed shop floor schedule.

» Clear statements and easy to understand terminology: TOC concepts like the goal or the operational measures, have been stated accurately and in clear terms. Additionally, most of the terminology employed make sense with the normal practices applied in industry for many years (common sense techniques and methods).

» Special attention is given to overall inventory: TOC demonstrates the direct relation inventory reduction has in the company's competitive elements (Goldratt and Fox 1986). Therefore, it uses the BM technique and the Rope concept to maintain WIP to a minimum and achieve a greater level of production synchronization.

» Benefits achieved: many benefits have been reported as a result of synchronizing the production process with the application of the TOC methods. Some of these benefits are:

- Considerable inventory reductions.
- Significant production lead time reductions.
- Elimination of production "waves".
- Quality improvements.
- Elimination of the "end of the month syndrome".
- Customer service improvement.

» TOC philosophy is still alive: since the late 1970s when TOC started to emerge, it seems as though if new concepts and methods are created every year. For example, Goldratt will release a new book in November explaining the TP soft system.

+ Weak points of TOC

» Radical management change: TOC application requires a radical management style change and complete conceptual reorganization to mould to the "revolutionary" methods that contrast greatly with the more traditional ones. A hard and long education process has to be carried out at all levels of the organization, and sometimes this represents the major constraint to be broken (see case studies).

» Lack of workforce involvement: TOC, being a centralized management philosophy focused primarily on production operations management, is normally top-down imposed. This may cause reluctancy in the workforce and the feeling that TOC brings new tasks that have to be fulfilled without clear reason (hence the importance of the education process).

» Is TOC an overall management philosophy?: some authors (e.g. Frizelle 1989) regard TOC as a technology more than an organizationwide philosophy. TOC is sometimes seen as a conglomerate of methods and techniques for the improvement of production scheduling.

» Indispensable requisites: Jones and Roberts (1990) identify the following requisites to be accomplished in order to successfully implement TOC:

- High volume, fairly stable environment, to be able to identify and exploit bottlenecks.
- Bottlenecks need to be forward loaded to 100% of their capacity.
- Demand is statistically stable.
- Employees will follow the schedule.
- Employers can follow the schedule.

» Narrow V-A-T scope: TOC's V, A and T plants classification does not contemplate the existence, for example, of project, job shop or continuous process production environments. TOC with its categorization of manufacturing systems seems to be only focused on batch manufacturing situations, with the possibility of being applied in certain line circumstances.

» Is AGI a "money making machine"?: the continual development of new production management methods (specially with the latest TP "soft system") can suspiciously be seen as an AGI (TOC originator and developer of the ideas) attempt to "make money". Further, the continual publishing of material in which old concepts are included among new ideas supports this argument (e.g. (1) Goldratt's and Cox's 1984 success with "The Goal" and reedition in 1993, (2) Goldratt's 1987, 1988 and 1989 journals in which few new concepts are included, (3) 1990's two books that revise former principles and analyze new others, and (4) Goldratt's latest book "It's not luck" -to be released in November 1994- reviewing TP).

However, TOC must be seen as an original philosophy that contains many useful theories concerning the production management insights and that has successfully changed the management style of many companies.

# 8 - EVALUATION OF DRUM-BUFFER-ROPE (DBR)

## 8.1 - Introduction

The "Drum-Buffer-Rope" (DBR) scheduling technique explained in section 6.6.8 is evaluated in this chapter. The following features will be assessed: firstly, the whole Drum-Buffer-Rope concept will be analyzed according to other authors' work and to the results of a production line operational behaviour study. Secondly, its suitability for balanced and unbalanced manufacturing systems is examined. Thirdly, DBR is compared with Linear programming and certain dispatching rules, and the performance of some reported cases under these scheduling techniques highlighted. Finally, the way particular production environments operate under DBR and other operation management techniques (among them MRP/MRP-II and Kanban) is analyzed through simulation and review other authors' work.

## 8.2 - Assessing the Drum-Buffer-Rope concepts

The Drum, Buffer, and Rope concepts are evaluated according to (a) some of the outputs of the operational behaviour of a production line under different production situations (see Appendix B) and (b) different authors' work.

The diversity of the possible production situations (see section 2.2) and their individual characteristics make impossible the evaluation of DBR in all of them. Therefore, the analysis of the operational behaviour of a production line under different simulated production circumstances was carried out, on one hand, to acquire the necessary knowledge of the performance of manufacturing systems under different modelled situations; and on the other hand, to examine the way the DBR logic addresses specific operational circumstances.

### 8.2.1 - Study of the operational behaviour of a production line

+ modelled production situations

First of all, in all simulation models restrictive assumptions have to be made in order to accommodate the realities of the system to an approximate model. Assumptions like, for example, the first machine is never starved of parts or the last machine is never blocked are commonly employed in such works. In the study in Appendix B, different production situations have been modelled to observe the behaviour of the production line under various circumstances. The production cases that have been analyzed and combined are:

» Balanced and unbalanced systems: a system is considered balanced when the total work content is evenly distributed over all the resources. On the contrary, an unbalanced plant contains some resources which are more heavily loaded than others (the heaviest loaded resource would be the CCR of the system).

» Synchronous and asynchronous systems: synchronous systems are those in which all the resources contain equal operation times and start and stop at the same instant (these systems are thus balanced). An example of a synchronous system are the automated car assembly lines. In contrast, asynchronous systems are subject to different process times, so that items cannot be transferred at the same time.

» Systems in which the resources are subject to process times fluctuations: in real manufacturing environments, process times are hardly ever deterministic and always contain a certain level of variability (this variability is illustrated in the models by Normal or Enlarg mathematical distributions). The result of fluctuations in the process times is lack of synchronization between the operations of the system.

» Systems with unreliable resources: machines or tools are subject to breakdowns and the randomness associated to their appearance is another factor that disrupts the normal production flow. Like the case of process times fluctuations, they also result in lack of synchronization between the operations.

» Buffered and unbuffered systems: buffers are employed to lower the negative effects of production disruptions in the final output of the system. They break production dependency so that production disturbances do not spread along the system (see section 7.4.3.1). The location and size of the buffers will greatly affect the performance of the whole system.

+ Results obtained from the study

It has to be noticed that (as in all simulation work), the results obtained are based on particular assumptions and depict individual production circumstances. Moreover, there are many factors that influence the production line behaviour that have not been contemplated in this study (e.g. set-up and transport times, demand variability, supply uncertainty, cost structure, etc..). However, the principles stated at the end of the study that illustrate the operational behaviour attributes give us an idea of how the system operates under different situations.

The two main outputs extracted from the study that will serve to assess the logic of the Drum-Buffer-Rope scheduling technique are related to the aspects that influence the production line efficiency and the way buffers can tackle them. The factors (that are given the name of principles in the study) that negatively affect production line performance are:

» The existence of a slow machine in the line (CCR)(principle 16). The machine with the lower relative capacity will determine the maximum output attainable for the whole line (if there is no efficiency loss, the production rate of the line will be the production rate of the CCR) and will mark the production pace for the whole system.

» The existence of variability in the machine process times. In principle-2 it is mentioned how this randomness results in output loss.

» Machine unreliability is another cause of production rate reduction. Machine breakdowns and the consequent repair times are one of the most important factors of the generation of disruptions.

» Failure randomness increases the creation and spread of production disturbances.

» Line length is another reason for output loss (principle-5). Although the output loss decreases with the line length, longer lines present more room for disturbances to spread than shorter lines.

» Other factors like set-up and transport-time variability, or operator task completion time randomness, also affect the line output.

A lot of research work has been spent by many authors analysing the appropriate buffer sizes and best buffers allocation patterns to improve line efficiency. Some of the conclusions obtained from their studies and own simulation work are:

» (Principle-6) Buffer capacities should be determined according to the variability amplitude of processing times, breakdowns, or repair times (according to the production disturbances degree).

» (Principle-7) Once buffer capacity have reached the level at which production disturbances are handled, further capacity increases will diminish the benefits obtained with their use (they have little marginal value after reaching the level at which variability is handled).

» (Principles-11/12/26) Balanced lines should have equal -or at least- symmetrical buffer capacity allocation. Additionally, better results are obtained when there is slightly more capacity in the middle ('bowl phenomenon') (assuming that the first resource is never starved and the last machine never blocked).

» (Principles-14/15/17) Buffers should be allocated according to the process times or repair times variability distributions (symmetrically or asymmetrically), and always surrounding the major source of disruptions (CCR).

» (Principle-18) When there is a severe CCR, the buffer capacity required is reduced because adjacent resource excess capacity protect the CCR from disturbances (this is valid assuming that material is released to the system whenever the first machine is idle). Buzacott (1971) claims that buffers are useful when there are variations between supply to it and demand from it.

» (Buzacott 1967, 1971) Buffers do not bring any benefit when there are external factors that affect the whole line equally (e.g. power supply failures, excessive rest periods, or labour difficulties).

### 8.2.2 - The Drum, Buffer and Rope concepts

The Drum, Buffer and Rope concepts will be assessed according to some of the outputs of the production line study just mentioned and with different authors points of view in the subject.

+ The Drum concept

The DBR scheduling technique stresses the role which capacity constraint resources have in determining system output. The Drum is the schedule that exploits the constraint in the best possible manner in order to answer external demand.

However, Goldratt (as creator of DBR) was not the first to discover that the production rate of the machine with least relative capacity (CCR) represents the maximum attainable output for the whole system. Authors like Buzacott (1967), Conway et.al. (1988), Dalley and Gershwin (1992), Glassey and Hong (1993), and Lambrecht and Segaert (1990) demonstrated this fact with their analytical and simulation work. As a consequence, in order to achieve maximum output, the CCR should be fully exploited.

The CCR can take any of the following forms: (a) highest workload of the system (slower machine, higher customer demand), (b) considerable number of breakdowns or long repair times, and (c) higher variability in process, set up, repair, or transport time than the rest of the resources.

» DBR contribution: DBR's contribution to the subject comes firstly from the underlying principles based on TOC concepts such us the 9 scheduling rules that not only identify the CCRs as throughput and inventory 'governors' (rule 6), but also define some guidelines in order to exploit optimally the CCR, and as a result, the whole system (e.g. batch overlapping should be encouraged to reduce inventory and production lead times, process batches should be variable, the CCR should normally have large process batches to reduce the time spent in set ups -primarily if the CCR is a bottleneck-, schedules should be established by looking at all the constraints simultaneously to avoid suboptimization, etc..).

Secondly, the Drum is not only established for the CCR, but also DBR identifies the key role assembly points and shipping operations (for the products that do not pass through the constraint) have in systems performance and create particular schedules for them.

Finally, DBR has a holistic vision of the system and pursues the company objective of increasing throughput, while simultaneously reducing inventory and operating expenses. The Drum in particular, determines the maximum attainable throughput by scheduling the more profitable products and by taking into account hard constraints (the static parts of the system), recognizing production dependency, resource and labour availability, machine capabilities, etc..

+ The Buffer concept

Buffers are utilized to protect system performance from the effect of production disturbances. DBR recognizes the existence of production disturbances (production phenomena: statistical fluctuations and dependent events) and employs time buffers to lower their negative effect.

The utilization of buffers against production disturbances has been proposed, for example, by Altiok and Stidham 1983; Buzacott 1967, 1971, 1972; Conway et.al. 1988; Dalley and Gershwin 1992; Gershwin and Shick, 1983; Gershwin 1987, 1994; Hillier and Boling 1979; Lambrecht and Segaert 1990; Owen and Mileham 1993. However, the buffers utilized in their studies are inventory buffers and not the "Time Buffers" defined by DBR (Cohen 1988; Goldratt 1984, 1986, 1990b; Srikanth 1987; Umble and Srikanth 1990). Related to this, Ronen and Starr (1990) declare that the Time Buffer concept has been discussed in Management Science/Operational Research (MS/OR) literature.

In addition, the dynamic nature of the manufacturing systems have been extensively studied by many authors (e.g. Buzacott 1967; Conway et.al. 1988; Donohue and Spearman 1993; Gershwin 1987, 1994; Glassey and Hong 1993; Hillier and Boling 1979; Hillier and So 1991; Owen and Mileham 1991).

The effect of production disturbances is in direct relation to the number of resources. In the previous section was stated that the higher the number of resources in the system the bigger the production output loss because production disturbances will have more room to interact (Conway et.al. 1988, Gershwin 1994).

Goldratt (1981) also maintains that the output lost due to production disturbances increases with the number of resources. The farther downstream the system, the more severe the magnitude of the disruptions and the bigger the output loss. In addition, according to Goldratt, non-CCRs excess capacity should be gradually increased towards the downstream end of the production process in order to tackle production disturbances and maintain the output rate dictated by the CCR.

The output rate of the system can be maintained either utilizing more protective capacity downstream the system or locating protective inventory (buffers) in specific parts of the plant. A comparison between DBR's buffer concept and the general guidelines of the buffer utilization aspects obtained from the production line study is shown in the following features:

» *Buffer location*: buffers should be allocated surrounding the major source of disruptions. This is, near the resources with less relative capacity (e.g. surrounding the CCR -Lambrecht and Segaert 1990-) or near the stations with higher variability (Conway et.al. 1988). The reason for locating the buffers in those places is because they decouple operation performances and stop the spread of production disturbances that would affect throughput and inventory.

In DBR, buffers are not only placed in front of the CCRs to protect them from disruptions; but they are also located in the places where disruptions are more likely to affect production schedules (i.e. assembly and shipping). Moreover, DBR relies on non-CCRs protective capacity ('catch up' possibility) to lower the effect of disruptions in the system performance.

However, DBR assumes that once parts are processed in the CCR will be processed at the succeeding resources without delays and does not consider the case of the CCR being blocked by production disturbances taking place downstream it. As a result, DBR does not surround the CCR -does not locate any space buffer after the CCR- and assumes that there is always enough room for the parts to be placed after it once they are processed. This may cause the stoppage of the CCR and the loss of systems throughput (specially if the system is close to balance).

- Close to balance situations: in the particular case of close-to-balance systems buffer capacities should be evenly spread between the resources (as disruptions can equally affect any part of the system)(Buzacott 1967, Gershwin and Shick 1983, Gershwin 1987, 1994, Owen and Mileham 1993).

DBR -like TOC- does not recognize the existence of balanced plants (Goldratt 1981) and thus, it cannot be applied in them (this fact is reviewed in the next section).

» *Buffer size*: buffer size (capacity) is influenced by the following factors:

(1) Buffer capacity should be proportional to the relative capacity of the CCR and the capacity of the rest of the system (Buzacott 1967, Conway et.al. 1988, Lambrecht and Segaert 1990).

(2) Once buffers contain enough capacity to protect the "weakest" parts of the system, increasing their capacity the benefits obtained by their use decreases (Buzacott 1967).

(3) Buffer capacity is substantially reduced when there is a severe CCR (i.e. when the capacity of the resources of the system is considerably higher than the capacity of the CCR). Non-CCR excess capacity will be utilized to "catch up" production when disruptions take place (Dalley and Gershwin 1992, Gershwin 1994).

DBR determines the size of the buffers (1) according to the relative capacity of the CCR and the capacity of the rest of the plant, and (2) according to the amplitude of the disruptions generated in the upstream resources. However, DBR (a) does not take into account space limitations while determining the buffer sizes in front of the CCR, assembly, and shipping (it assumes that the buffer capacity is infinite) and (b) does not contemplate the amplitude of the disruptions in downstream resources.

The strength of the DBR buffer concept comes from its time buffer definition that links the Drum with the material release operation. By doing so, downstream operations are activated according to the schedules of the critical parts and inventory is kept only to the minimum required to avoid those resources being starved of material.

+ The Rope concept

The material release schedule (Rope) is determined by subtracting the time buffers from the schedules of the critical resources (CCR, assembly and shipping). The Rope thus, takes into account production disturbances and release material to the systems ahead on time so that critical resources are not starved of parts.

In a way, this concept can be considered similar to MRP/MRP-II's backward schedule from the final products due dates and the 'inflated', fixed production lead times utilized to protect the system from production disturbances. However, DBR's Rope concept differ in that (a) it recognizes the system finite capacity by only releasing work at a rate which can be accommodated by the critical resources, and (b) it places the buffers only in the places where they are more beneficial (not everywhere as in MRP/MRP-II).

As a conclusion, although the Drum-Buffer-Rope concepts in isolation may not represent a new contribution to the scheduling subject. DBR's major contribution is the way it brings these concepts together.

### 8.3 - Assessing DBR application in balanced and unbalanced systems

In the following two sections, the suitability of Drum-Buffer-Rope scheduling technique for the two of the most general production situations (balanced and unbalanced systems) is assessed using simulation models when appropriate.

#### 8.3.1 - Applying DBR in balanced systems

Goldratt (1981) declares that balanced plants seldom exist because of the disruptive effect of production disturbances. Statistical fluctuations coupled to dependent resources will spread along the system and will give rise to three phenomena:

- "Wavelike" production behaviour: the wave production pattern is characterized by an erratically oscillatory pattern in the transfer of parts between resources. Instead of a smooth production flow, resources will be sometimes overloaded and other times idle. Moreover, the farther downstream in the system, the more severe is the magnitude of the wavelike pattern.

- "Wandering bottlenecks": this phenomena occurs as a result of poor scheduling or wavelike production behaviour. The result is large temporally loads in certain resources. In reality, these resources have enough capacity to cope with the demand placed on them, but cannot answer to temporary overloads.

- Interactive constraints: in balanced situations, it is common to have more than one constraint. These constraints will interact with each other and jeopardize system throughput (if they are not properly handled).

Although in an ideal world a balanced plant would be the best arrangement, in the real world where statistical fluctuations and dependent resources take place, "..the achievement of a truly balanced plant would lead to rapid bankruptcy" (Goldratt 1981). In a balanced plant containing production disturbances, the resources do not have excess capacity to 'catch up' production when disruptions take place. This leads to: (a) an increase in WIP which grows ever larger with time, (b) an increase in production lead time that will also grow with time, and (c) a reduction in throughput since production lead time is continually growing. (Since the gap between the first and last resource is growing ever larger, the last resource is processing most slowly -Goldratt 1981-).

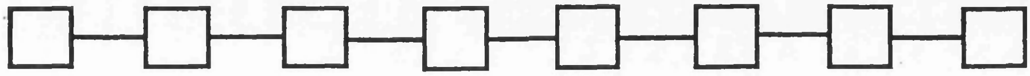
Model I (shown on the next page) illustrates a balanced production line in which material is released to it when the first resource is idle. The results of the simulation demonstrate that WIP and lead time grow larger with time. However, the efficiency of the last resource -and thus line output- remains approximately the same in all the simulation results checked (about 99.4%) since with the growth of WIP in the system, production dependency is 'almost' broken and the resources act independently.

+ DBR and balanced systems

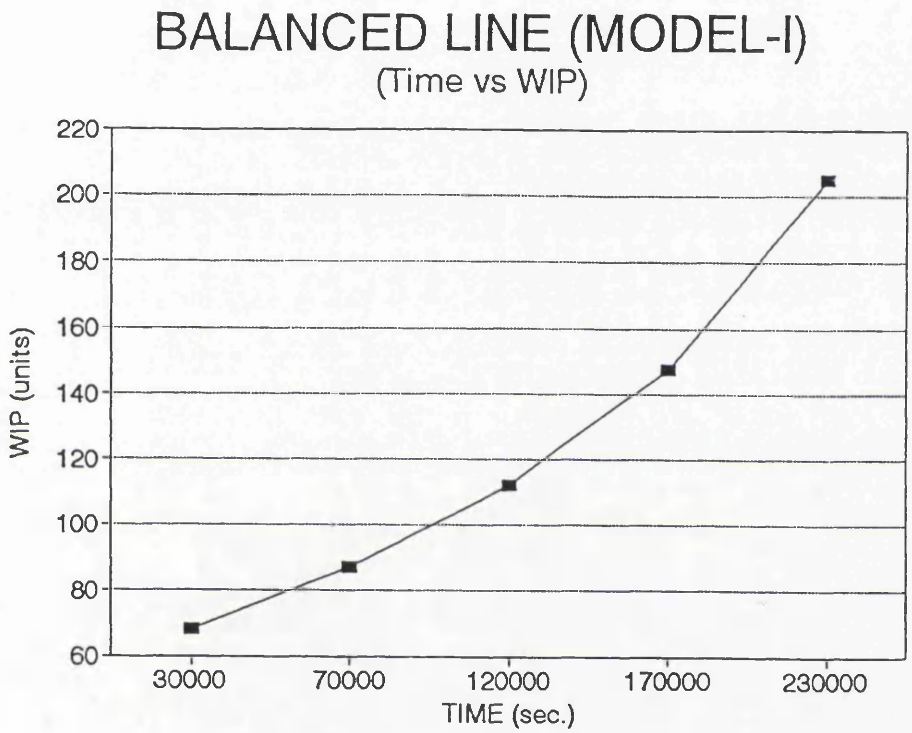
From what has been already stated, balanced, or even close to balanced plants, will be difficult to manage not only for DBR but for any other production management approach. The reasons why DBR scheduling technique will not be successfully implemented in balanced systems are:

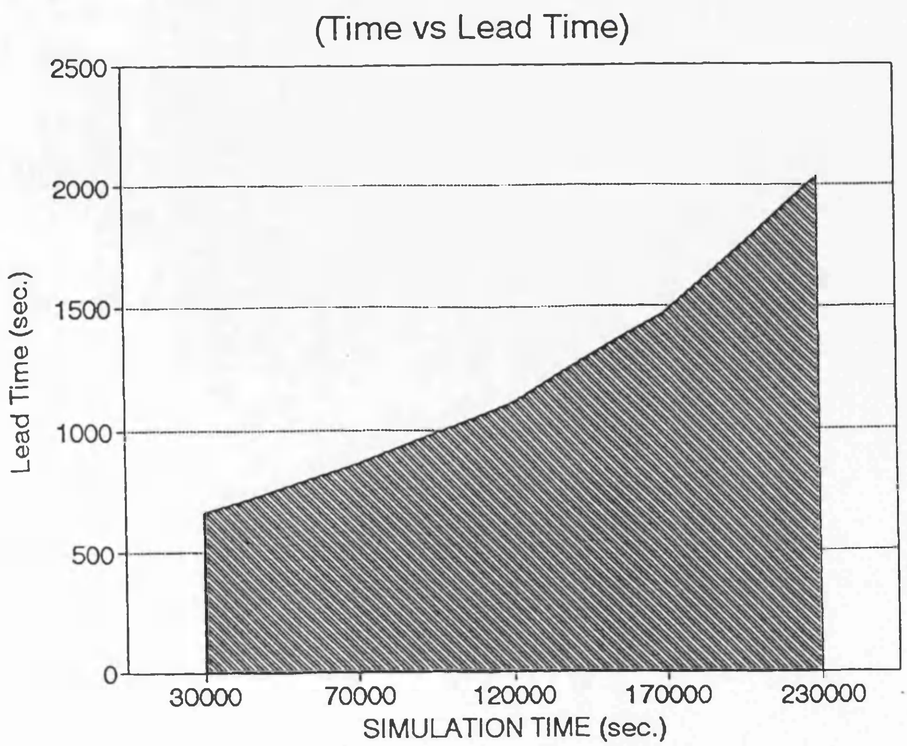
1- All the resources of the system have the same production potential and therefore, there is not a single Capacity Constraint Resource in the system (or maybe all of them should be considered as constraints) in which focus attention in order to improve the whole plant. (The Drum cannot be created).

# MODEL - I



* Process Times= Normal distr. (C, var.)
  ALL> C=10sec. and var.=2.5sec.
* Buffers of infinite capacity between all the stations



2- As production disturbances affect equally all the parts of the system, buffers should be evenly spread (in consonance with the results of Appendix B -principle 11-).

3- If a Drum cannot be created or Time Buffers are impossible to define, there is no possibility for determining the Rope.

However, it has to be mentioned that in close-to-balance real manufacturing environments (e.g. continuous processes or some production lines), DBR could be applied with the final product demand acting as the Drum, and releasing the material to the system certain amount of time (Time Buffer) ahead its due date.

### 8.3.2 - Applying DBR in unbalanced systems

Unbalanced systems are characterized as having some resources more heavily loaded than others. The heaviest loaded resource would be the capacity constraint resource (CCR) of the system. The following two cases that can take place in unbalanced systems are examined in the next sections: (1) the existence of a 'clear' CCR, and (2) the existence of two or more resources with similar relative capacity (i.e. interactive constraints).

#### 8.3.2.1 - Unbalanced systems with a 'clear' constraint

In the cases when the relative capacity of a particular resource is considerably higher than the capacity of the rest of the resources (e.g. when there is a severe constraint), in theory, the Drum-Buffer-Rope scheduling technique would be successfully applied:

1- The constraint of the system will -normally- be easily identified and the schedule that exploits its available capacity created (Drum).

2- The Drum will then be protected (a) by the excess capacity of its adjacent resources (protective capacity, 'catch up' capability), and (b) by a buffer located in front of the critical places (Time Buffer).

3- Material will be released to the system according to the Drum and certain amount of time before it is required in the critical resources (Rope).

The manufacturing environments that are normally characterized for having certain unbalance degree are project, jobbing, batch and certain production lines. The difficulty to apply TOC's management concepts -included DBR- in unstable production environments and production systems with variable processes (typical project and jobbing situations) was mentioned in section 7.4.5. Therefore, DBR seems to be more applicable for batch and certain production line situations. The case studies included in Appendix A demonstrate this fact. DBR has been successfully applied in:

» Complex batch manufacturing situations (case 1 -A plant-, case 2 -V plant-, and case 3) in which, in general, throughput was increased, inventory reduced, production lead times reduced, and customer service improved through a better due date performance.

» Assembly lines (cases 6 and 7) where Kanban was replaced by DBR and, as a result, in both cases throughput increased by protecting the final assembly from disruptions.

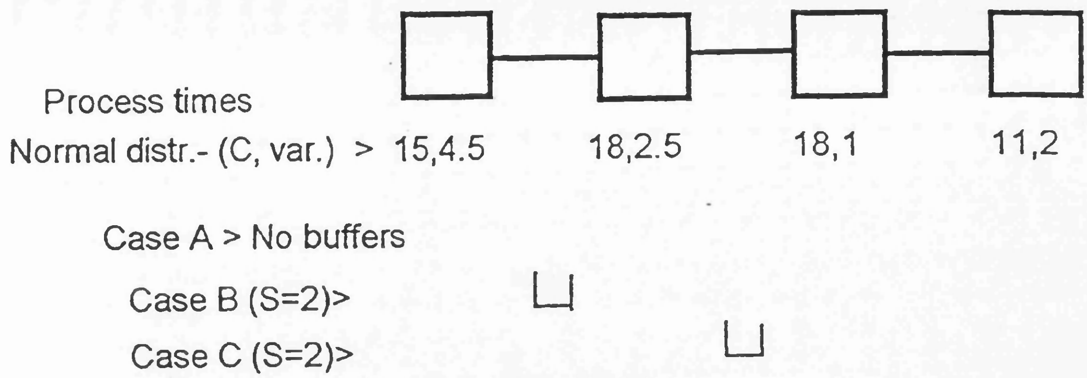
#### 8.3.2.2 - Unbalanced systems with interactive constraints

Interactive constraints occur when the relative capacity of two -or more- resources of the system is so similar that the production pace of individual constraints is conditioned by the production pace of the other constraints (they interact with each other). When interactive constraints take place in a system that contains production disturbances, system output is highly threaten. They have to be carefully scheduled (so that the optimization of one constraint does not suboptimize the others), and buffers have to be adequately located to avoid their stoppage as a result of their interaction and the effect of production disturbances.

DBR does not apply particular measures for the case of interactive constraints. It simply maintains that the Drum should be created to exploit the largest CCRs (taking care that the rest of the resources are not suboptimized in the subordination process) and time buffers should be located in front of them.

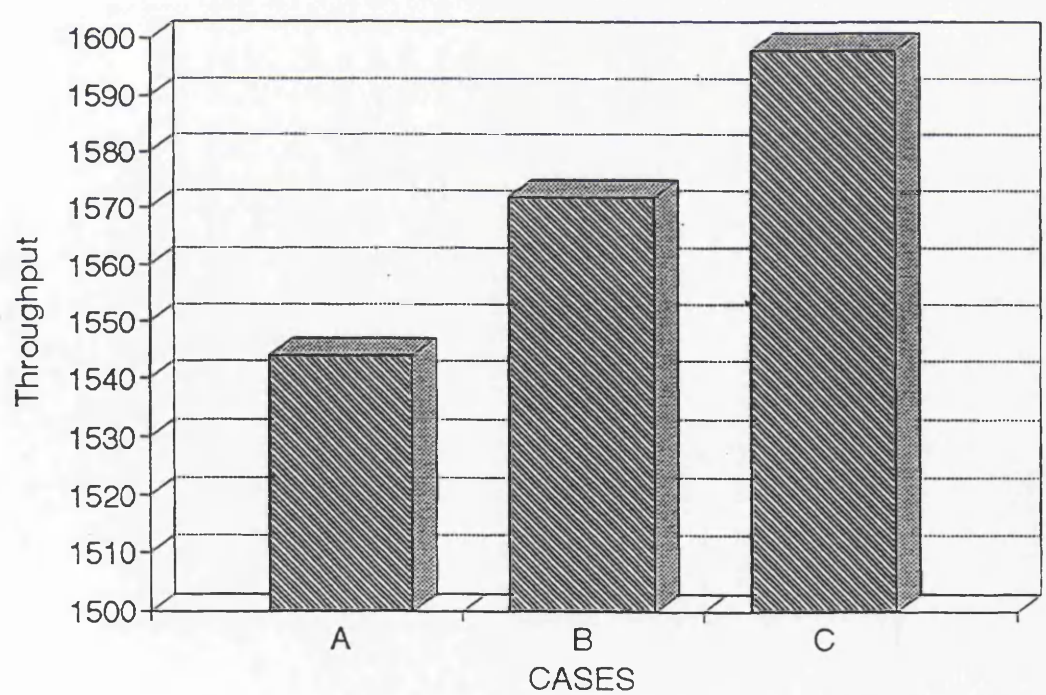
In the following production line models simulated in WITNESS it is shown how allocating the buffer between two interactive constraints -instead of locating it in front of the largest CCR as DBR proposes- provides better results. The reason for this is that buffers are employed to decouple operation performance (break dependency) and stop the spread of production disturbances. Therefore, they should be located between the two major sources of disruptions so that the system is separated in two halves and the negative effects of production disturbances cannot accumulate. Moreover, according to the simulation models carried out, when there are several resources between the two CCRs, buffers should be placed in a way that divide the system in two halves (see Model III).

# MODEL - II

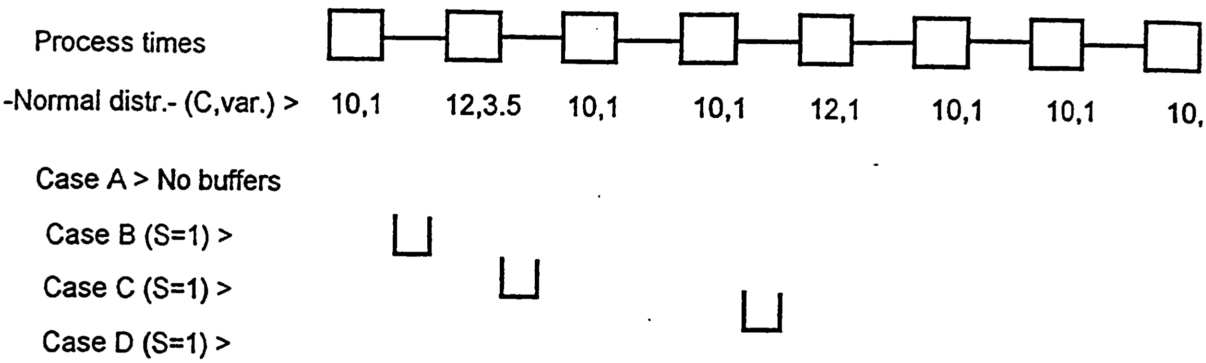



## INTERACTIVE CONSTRAINTS (MODEL-II)

(Throughput vs Buffer location)

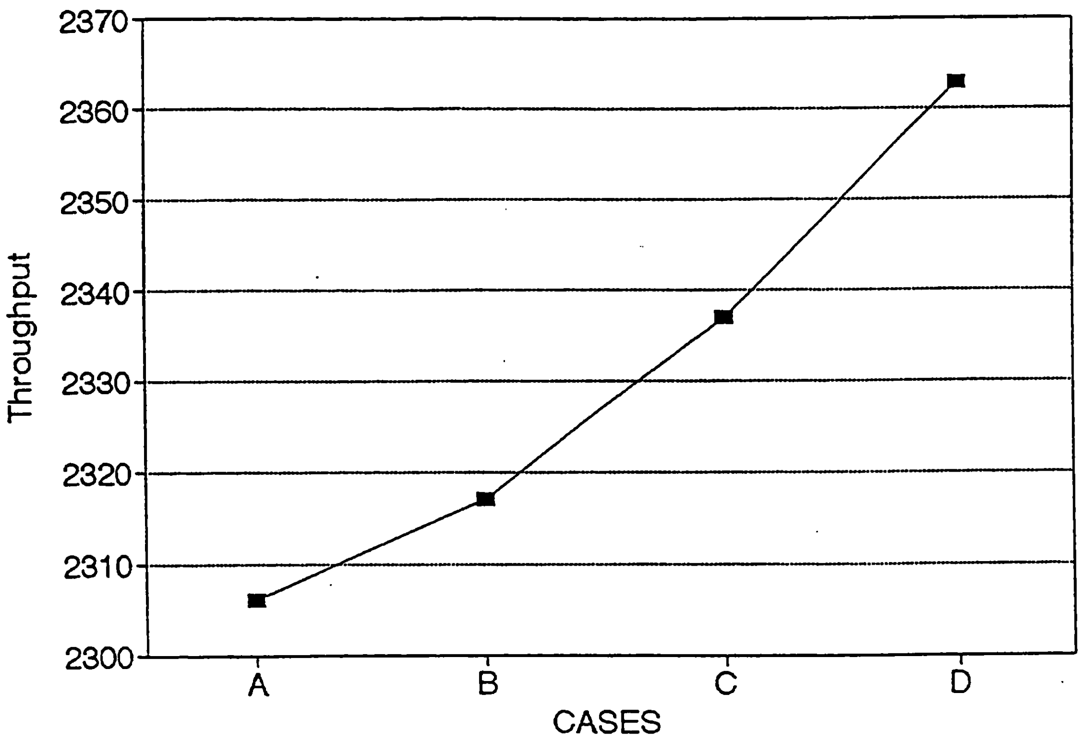


## MODEL - III




# INTERACTICE CONSTRAINTS (MODEL-III)

(Throughput vs Buffer location)



+ Alternative solution

Ronen and Spector (1992) maintain that modern management philosophies like JIT and TOC, place strong emphasis on operations management and do not provide sufficient tools to consider the economic outcomes of the techniques applied to achieve an effective flow of materials. They propose an alternative solution called "cost/utilization approach" that combines the Pareto approach with the DBR technique.

The cost/utilization approach suggests locate a buffer after a "noisy" resource (a resource with high variability), instead of in front of the constraint of the system. This will dampen system fluctuations and increase production capacity at a lower cost than locating the buffer -farther in the system- in front of the CCR. The "cost/utilization" alternative is validated in Model IV. However, Model V demonstrates that this solution would not bring the desired results when the relative capacity of the noisiest resource is slightly lower than the capacity of the interactive constraints. In this last case, better results are obtained locating the buffer between the two constraints.

+ Summary

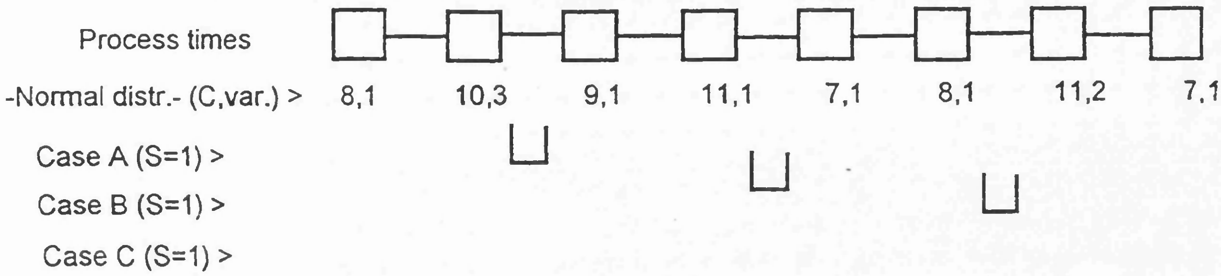
As a summary, the following guidelines related to the buffer location in unbalanced plants with interactive constraint can be drawn:

- When there are two severe interactive constraints, buffers should be located between them -even if there is a noisy resource in the system (Model V)-. Moreover, the buffer should be located so that the system is divided as close as possible in two halves (Model-III).

- When there is a noisy resource whose capacity is close to the CCRs capacity, buffers should be located after the noisy resource (cost/utilization approach -Model IV-).

- When the system is far from balance and there is a clear, single CCR, locate the buffer in front of it (DBR technique).

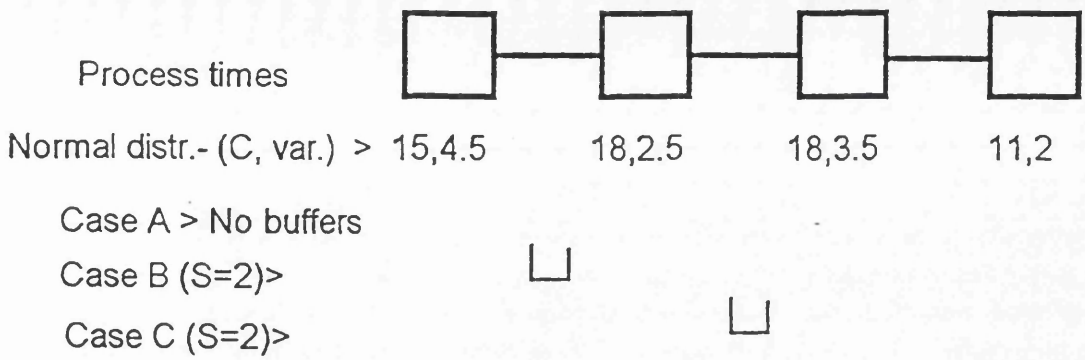
# MODEL - IV




## INTERACTIVE CONSTRAINTS (MODEL-IV)

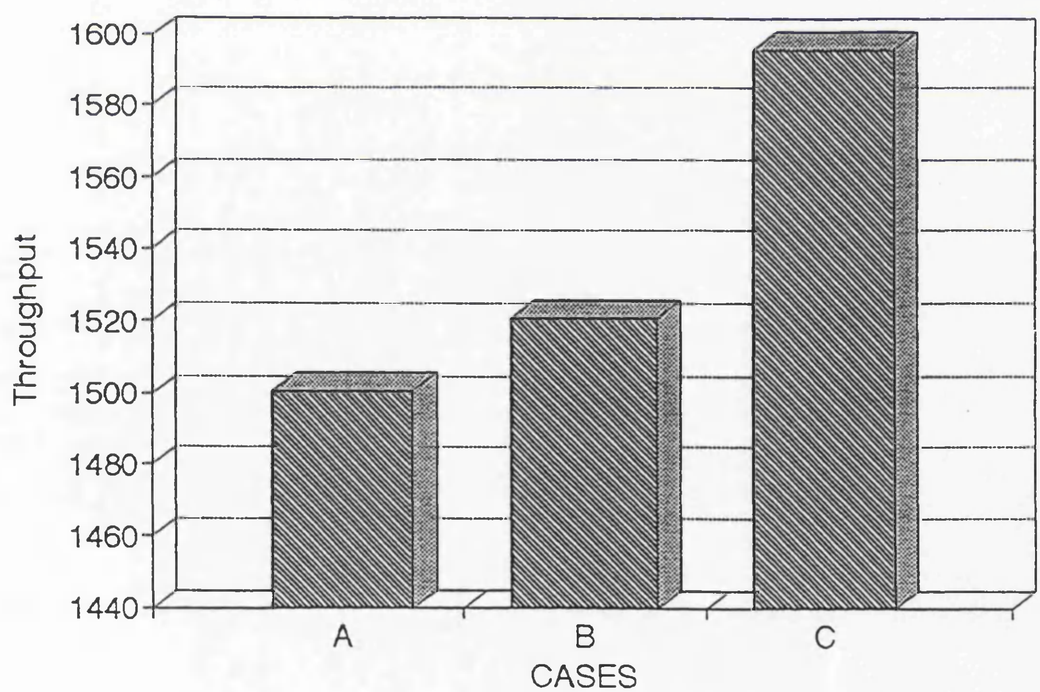
(Throughput vs Buffer location)

# MODEL - V




## INTERACTIVE CONSTRAINTS (MODEL- V)

(Throughput vs Buffer location)



## 8.4 - DBR and other production scheduling approaches

### 8.4.1 - DBR and Linear Programming

Linear programming (LP) can be defined as a mathematical technique that represents the scheduling problem as a set of linear equations and obtains a solution that achieves the objective function by solving all the problems.

Some authors maintain that linear programming will produce the same solutions that those obtained applying DBR, and thus, that this technique does not bring much new in the scheduling problem solving field. For example, Ronen and Starr (1990) state that "the idea of bottleneck and non-bottleneck resources can be viewed as a special case of mathematical programming". Scarce and non-scarce resource terms employed in linear programming will be identified as TOC's bottleneck and non-bottleneck resources. To illustrate this point they present a very simple example of a manufacturing situation formed of two final products and five operations, and demonstrate that the same solution is obtained applying LP and DBR.

Plenert (1990) states that DBR calculation "is inefficient when multiple constrained resources exist" and that "linear-integer programming is a much better planning tool and comes closer to achieving the TOC goal of maximizing throughput" when the multiple constraint situation arises. He demonstrates this statements by comparing DBR's and LP's solutions in three different manufacturing models: (1) the first model is a simple example of 2 final products, 4 raw materials and 8 different operations, in which DBR and LP obtain the same solution. (2) In the second model the above situation is tightened to the extent of creating three constraints. DBR in this case comes up with a less optimal product mix than LP. (3) The third model is a more complicate production situation formed of 4 final products, 6 raw materials and 19 operations. DBR in this case produces an unfeasible solution in which the capacity of two of the constraints is exceeded.

On the other hand, Luebbe and Finch (1992) highlight the conditions that must be met to make LP applicable. These are: existence of an objective function, limited resources, linearity in the relationships between the variables in the objective function and constraint equations, and homogeneous products and resources. They -surprisingly- compare TOC with LP and maintain that although both DBR and LP can be used to determine the optimal product mix under a given set of circumstances, TOC is an overall philosophy, which utilizes a number of specific techniques, whereas LP is an optimization technique -something obvious-. Therefore, they declare that the level of analysis provided by LP is not as detailed as TOC's "$ return/constraint unit" analysis, and that LP does not provide the TOC focus on improving the component that limits the organization ability to make money (i.e. the constraint).

The above examples demonstrate that in particular circumstances LP can produce better results than DBR (in terms of more profitable products mix). However, DBR surpasses LP capabilities by having a more realistic view of the behaviour of the production environments in the sense that tries to manage efficiently the shop floor stressing the role which constraints have in the performance of the system (something overlooked by LP).

### 8.4.2 - DBR and the heuristic approaches

Drum-Buffer-Rope scheduling technique should be considered a heuristic approach. This approaches are characterized by sequencing the jobs to be processed at the resources according to certain rules (e.g. First-in-first-out, minimum total processing time, earliest due date, etc..)(see section 4.3). Heuristic techniques can be divided into (a) priority rules (priorities are assigned to the jobs waiting in front of the machines according to some rules), (b) heuristics or dispatching rules (they are "rules of thumb"), and (c) scheduling rules or heuristic programs (they combine simple heuristics with a procedure to derive a solution from them).

DBR has to be included in this last group. However, most of the heuristic rules -specially the dispatching rules- are characterized for being "myopic" (they sequence the jobs in the machines without taking into account the production situation in the rest of the system -lack of holistic vision-). While DBR, first creates the Drum for the critical parts of the system, and then, subordinates the rest of the plant to that Drum. Additionally, in contrast to traditional scheduling rules, it includes measures to protect the schedules (time buffers).

+ Reported studies

In the following two cases a simulated plant is run under particular DBR applications and simple dispatching rules in order to compare its performance:

» Case 1: Neely and Byrne (1992) analyze the production performance of a simulated plant under six different heuristic rules: FIFO, total operation time (higher priority is assigned to the job with longest total operation time), batch operation time (higher priority assigned to the batch with shortest operation time), batch operation time plus set up time, total operation time/batch operation time, total operation time/batch operation time + set up time. The simulation consisted of scheduling 20 batches of work, each of a different product, in 9 machines under the above heuristic rules.

The batches were also scheduled applying what they called "bottleneck scheduling". Bottleneck scheduling simply consisted on always giving priority to the jobs due to go through the CCR at some stage in their routing. Bottleneck scheduling rushes work through the bottleneck and avoids long queues of jobs in front of the constraint. The final results showed that there was a trend for throughput to increase and inventory to decrease when bottleneck scheduling was used. Moreover, the best results were obtained when batches that tied up the bottleneck for the least time were loaded first.

» Case 2: in a recent article Wu et.al. (1994) simulate the performance of a hypothetical furniture manufacturing case under DBR and what they call "cutting" approach. The "cutting" approach consists of scheduling as early as possible all the parts associated with an order (this approach is represented in the simulated model ranking jobs on the basis of the most subsequent operations first -MSOF-).

The final results of the simulation show that DBR produces the final products with nearly 30% less time than the "cutting" approach and that the identified CCR is fully utilized with DBR, while with the "cutting" approach it is sometimes starved of parts.

### 8.5 - DBR and other operation management techniques

DBR operating procedure is compared in this section with other operation management techniques (e.g. MRP/MRP-II and Kanban) through the analysis of the results obtained from reported and my own simulation models.

+ Reported simulation studies

Some of the simulation studies comparing -sometimes particular- DBR applications with other production management techniques are:

1- Lambrecht and Decaluwe (1988) employ XCELL software to compare the way a fictitious plant would run with Kanban and with what they call SYN -synchronized- (a simple approach, based on Goldratt ideas, that stresses the role of the constraints). They demonstrate that the system performs better with SYN when production demand increases notably and production attention is put in full constraint exploitation.

2- Ramsay et.al. (1990) compare the pull approach (JIT/Kanban), push approach (MRP), and the "squeeze" approach (DBR) in a complex simulation case. At the end they conclude that the squeeze approach is the most useful of the three, without providing explicit results.

3- Raban and Nagel (1991) simulate the production performance of a flexible flow line under three demand loads. The results obtained applying TOC, hierarchical control algorithm (based on events time decomposition), and Constraint Based Control strategy -CBC- (combination of the strengths of TOC concepts with the hierarchical control algorithm) demonstrate that CBC performs better than the other two. CBC obtained a production performance closer to 100% when the product demand loaded the system also to 100%.

4- Byrne and Jackson (1994) investigate the impact the introduction of some TOC concepts have in a company employing MRP. They simulated the shop floor manufacturing operations and they found that a serious bottleneck existed in one machine in a system of eight machine groups. Sensitivity testing revealed the dramatic effect on total system performance of increasing the bottleneck capacity. When the bottleneck was eliminated and the mean and variance of process times reduced: (a) throughput increased, (b) inventories were reduced, and (c) MRP schedule adherence improved significantly.

5- Lambrecht and Segaert (1990) analyze the production performance of different production lines under different buffer stock allocations that resemble Kanban, MRP and DBR operating manners. DBR technique is modified by limiting the capacity of the buffers upstream of the constraint, but allowing the location of parts between any of the upstream resources (they call this method "long pull"). The final results show that long pull achieves the highest throughput but employs large inventory buffers.

+ Simulation models

Three models have been created to compare DBR with other operations management techniques. These models are:

» Model VI: a balanced assembly/merging line formed of 12 stations is utilized to allocate the same buffer capacity but in different patterns: (a) Kanban (buffers of 2 units of capacity are placed between all the resources and the stations are activated when the buffer contains only 1 unit -trigger/processing sign-), (b) MRP (equal buffer allocation -2 units-), and (c) high inventory environment (there is a maximum buffer capacity of 20 units that can be placed anywhere in the system). The process time distribution is Normal and it is subject to different variability. Material is released to the system when the first resource is idle, and products are shipped when the last resource finishes processing them. The final results show that when process times contain high variability, the high inventory environment (in which buffers can spread evenly along the system) achieves the highest throughput -but with the highest inventory-.

» Model VII: an unbalanced line containing 8 stations and a severe constraint is employed to simulate: Kanban (S=2 and Trigger=1), MRP (S=2), high inventory environment (S.tot.= 14), and DBR (a buffer with a maximum capacity of 8 units is located in front of the CCR which allows the release of material when it reaches 2 units -trigger/Rope-). Process times are subject to high variability (Negative Exponential distribution) and the simulation is runned for more than 30000 seconds to obtain reliable results. The outcome of the simulation is a highest throughput achieved in the high inventory environment, but with DBR in second place and utilizing much less inventory.

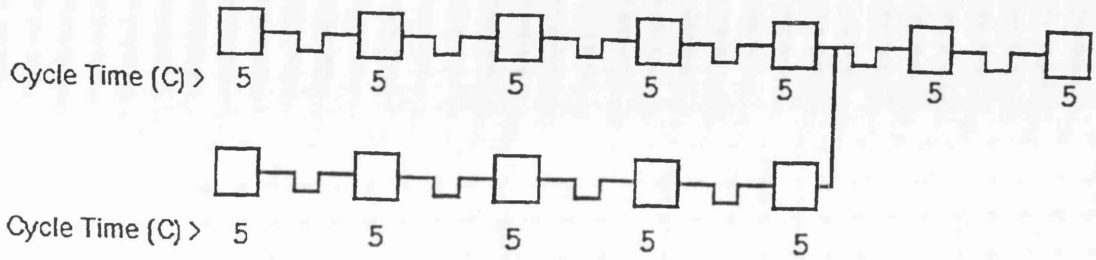
» Model VIII: an unbalanced merging line with very variable process times (Neg. Exp.) and a significant constraint is employed to simulate: Kanban, MRP, DBR (6 units maximum buffer and a Rope -trigger- of 3), and two high inventory situations:

- S.Tot.=20 > maximum buffer of 6 units anywhere upstream of the CCR, and buffers of 2 units between all the other resources.

- *S.Tot.=20 > maximum buffer of 6 units anywhere upstream of the CCR, another maximum buffer of 10 units anywhere in the branch upstream assembly that does not contain the CCR, and buffers of two units between all the other resources.

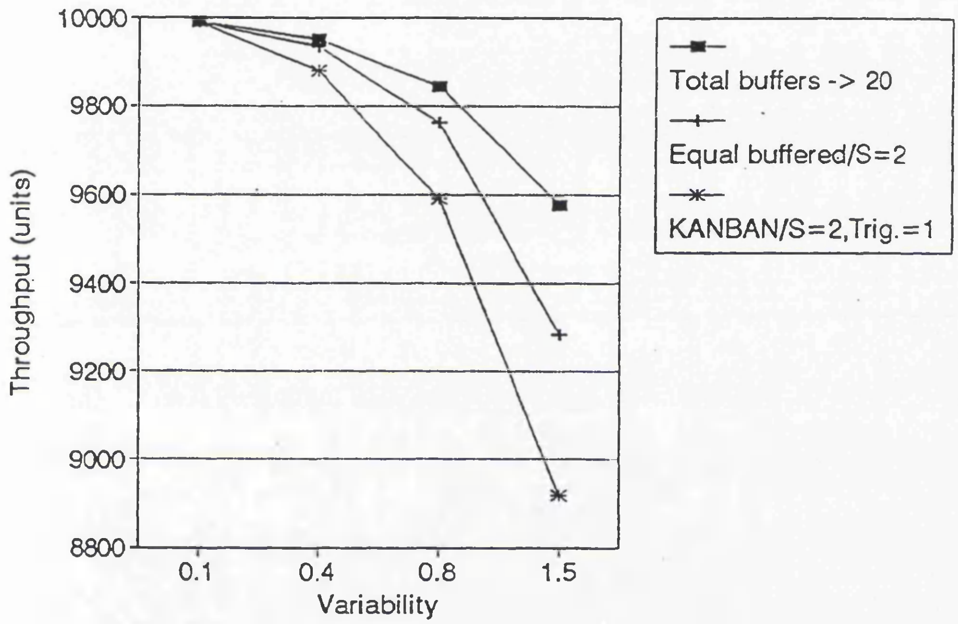
The final results indicate that *S.Tot. achieves the highest throughput but employs considerable inventory. DBR on the contrary, is in second place with considerably lower inventory.

# MODEL - VI

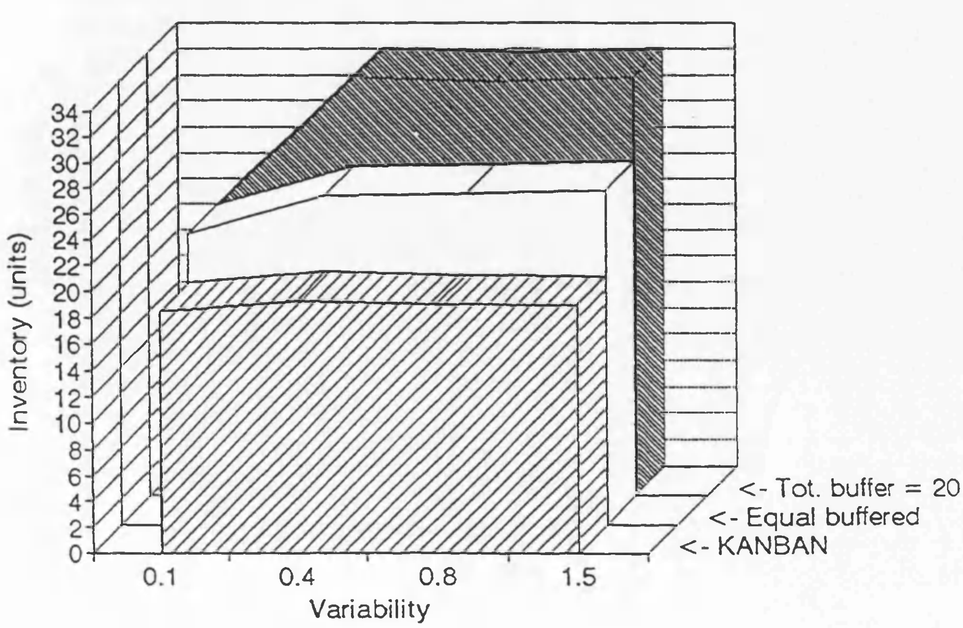



## BALANCED MERGING LINE

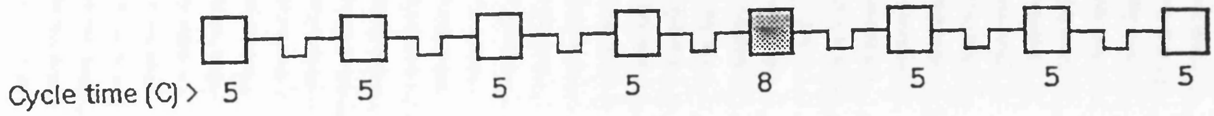
(Output)




(Inventory)

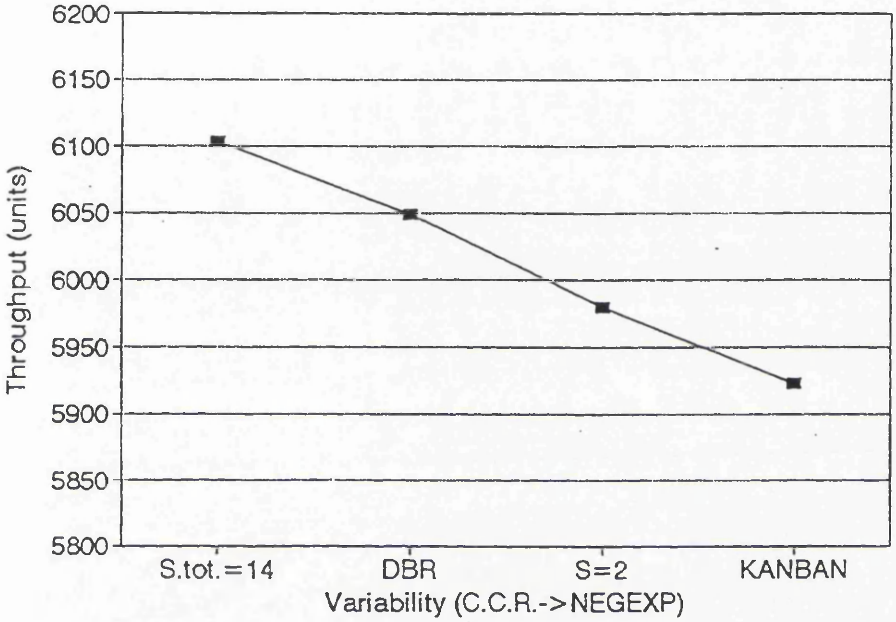


# MODEL - VII

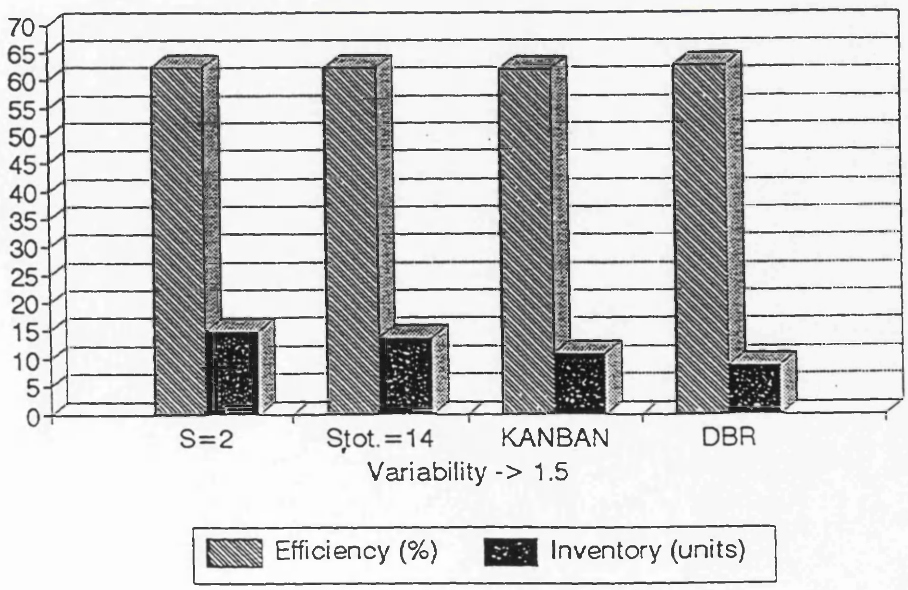



## UNBALANCED LINE

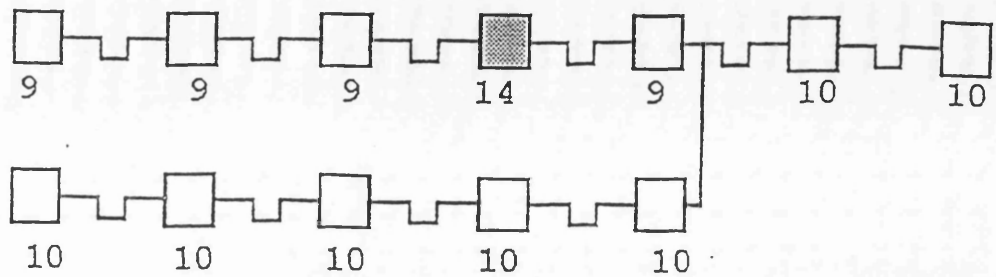
(Output)




(Inventory vs Line efficiency)

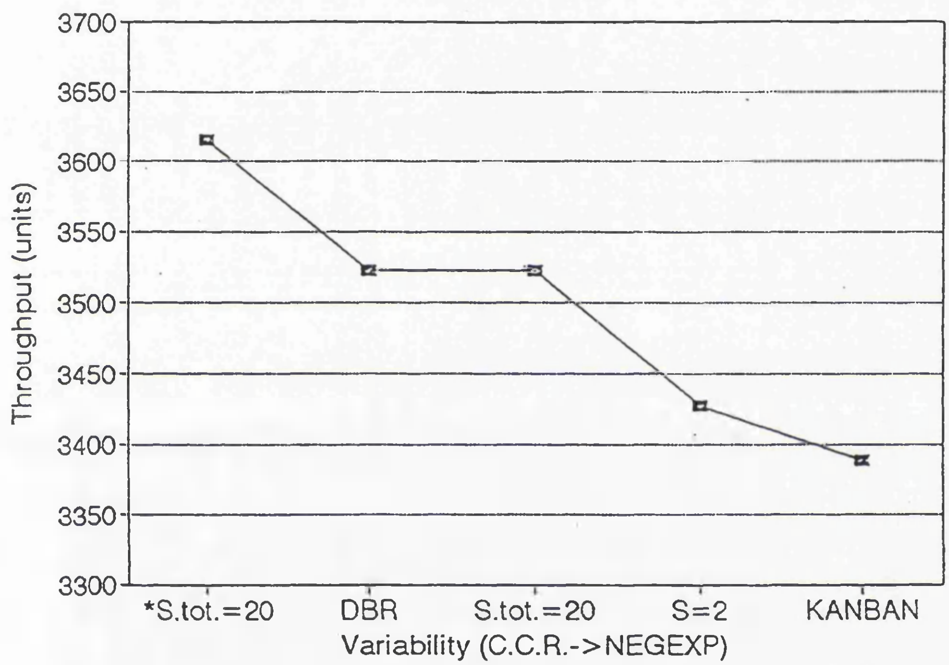


## MODEL - VIII

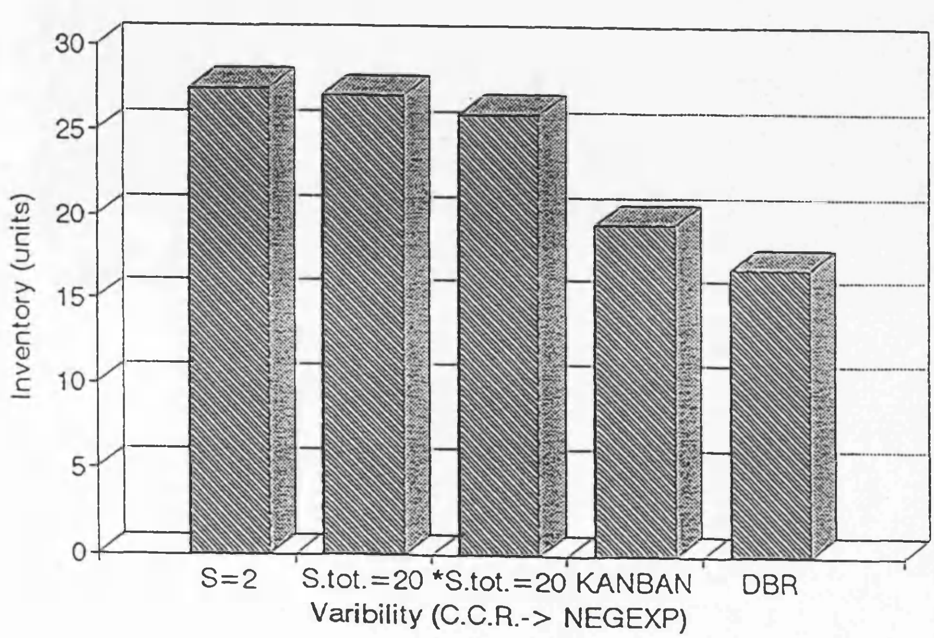



## UNBALANCED MERGING LINE

(Output)




(Inventory)



## 8.6 - Conclusions

The following conclusions are related to the Drum-Buffer-Rope scheduling technique:

1- The Drum, Buffer and Rope concepts in isolation do not represent a new contribution to the scheduling field. However, the three of them together form a new idea for the solution of the detailed shop floor scheduling problem.

2- Based on DBR's scheduling logic and on the reported case studies, this technique seems to be more suitable for unbalanced production systems than for balanced -or close to balance- ones. The whole Drum-Buffer-Rope concept is more likely to be implemented in such plants and the benefits from a synchronized production flow achieved.

However, according to the simulation work performed, for the case of interactive constraints, better results (in terms of increased throughput) can be obtained by applying other logic rather than DBR.

3- Comparing DBR and Linear Programming (LP), in specific reported cases, LP generated better results than DBR. Nevertheless, DBR provides additional insights in the management of the shop floor operations by stressing the role constraints have in the overall production performance.

4- In some published papers, DBR seems to be a better solution than some simulated dispatching rules. This could have been intuitively anticipated taking into account the "myopic" view of the dispatching rules. (They look at individual events without taking into account future consequences). This is in contrast to DBR's holistic vision of the system that focuses on the CCRs and subordinates the rest of the resources to their schedules.

5- Finally, based on my simulation work and other reported cases, DBR should be considered a good production management solution, mostly because it reduces inventory and achieves high -if not the best- level of throughput.

# 9 - OPT SCHEDULING SOFTWARE

## 9.1 - Introduction

The Drum-Buffer-Rope scheduling technique requires the support of computer software to manage complex scheduling situations and handle large amounts of data. Optimised Production Technology (OPT) scheduling software was created in Israel during the 1970s by a group led by Dr Eliyahu Goldratt. It incorporates DBR ideas and has achieved considerable success in its spectacular evolution.

In section 6.2 was pointed out how OPT was the root from which the whole TOC management philosophy evolved. In its early days, it behaved like an automated Kanban (maintaining inventory to a minimum and producing only the items required from the market). New production management concepts were included in the software (e.g. bottleneck resources, 9 scheduling rules, DBR, Time Buffers, different batch sizes, etc..) to create a powerful finite capacity scheduling package. Nowadays, OPT should be considered as a "bottom up" system that applies DBR scheduling technique for the efficient management of shop floor operations.

Only one OPT software version is currently marketed by Scheduling Technology Group -STG- (OPT distributor): OPT21 (targeted at large and medium size companies). (In the past OPT5000 -specially developed to enable small companies apply TOC principles with a lower cost- could also be bought, but is no longer in the market).

+ Capabilities and claims

According to Jacobs (1983) and Meleton (1986) OPT vendors declare that the software is capable of: modelling the intricacies of any manufacturing environment, generating material and capacity requirement plans, and producing near optimal finite schedules that sequence jobs and set process and transfer batch sizes. In addition, management can include its particular policies so that OPT schedules can focus, for example, on lowering costs by minimizing setups, smoothing production flow by reducing the transfer batches, or by improving delivery performance at the expense of setup costs. Finally, due to quick run-times, OPT can be used as a simulation tool to: (a) plan long-range production and capacity situations, (b) model manufacturing environments (e.g. plant consolidations, facility rearrangements, and bottleneck management resolutions), and (c) test production outputs at various factory loads, setup times, or different shop floor configurations.

Further claims about OPT's "extraordinary" capabilities are (Fox 1985). It:

- Can create typical MRP and capacity functions and generate accurate, detailed schedules for each manufacturing resource.
- Produces realistic schedules that are immune to the unpredictable events.
- Generates the more profitable schedules of any commercially available system.
- Has an online inquiry system that responds to inquiries in seconds.
- has an implementation period between 3-5 months in order to create schedules that would generate good bottom line results.
- Runs very quickly on even mini computers ('What if' simulations are claimed to be performed in minutes).
- Is a standard software package for all types of manufacturing situations.
- Is user friendly and can be used by the operating people in all sort of plants.

+ OPT users' opinion

In contrast to the above claims, the major weaknesses of OPT reported by its own users are (Fry et.al. 1992): (1) it is not user-friendly, (2) it requires extremely accurate -dynamic data- and timely feedback, (3) it is overly sophisticated, (4) it has prohibitive maintenance costs, and (5) its results are not intuitive. Furthermore, the following negative aspects arise from OPT implementations (Jones and Roberts 1990): (a) OPT software is not cheap and involves putting a firm's faith in just one company, (b) it is not user friendly and needs a high degree of analytical skills, (c) although OPT can be implemented fairly rapidly, it will take up to a year or more for a company to become completely familiar with it, and (d) a lot of time and effort has to be put into setting up systems to supply the accurate data needed by OPT.

However, OPT has brought enormous benefits for most of the companies that have implemented it. OPT's strengths are (Jones and Roberts 1990): increased motivation of workforce at all levels, improved relationship with outside suppliers, quick results (9-12 months). Other strong points are (Fry et.al. 1992): explicit recognition of bottlenecks, effective reduction of cycle times and WIP, and its basis in the TOC philosophy, which is an excellent training tool for workers.

Finally, OPT has to be seen as an operational tool for planning and scheduling production, and an analytical technique for simulating and optimizing production operations that embodies TOC concepts and that can provide significant benefits.

## 9.2 - OPT approach

### 9.2.1 - Scheduling fundamentals

In 1980, Goldratt declared that the scheduling process should be viewed as a three interconnected stage process:

1- Setting the batch size: the Economic Batch Quantity (EBQ) batch sizing technique has been broadly employed to determine the production lot that will originate the minimum cost per part. The EBQ is obtained by balancing two competing tendencies: (a) the saved setup time and labour cost achieved by increasing the batch size, and (b) the increase in lead time and inventory carrying cost as a result of large batches. But the fallacy of this technique rests on the assumption that the saved time for setting up one batch can be used for another batch. The role CCRs play on managing and controlling the production process is ignored.

TOC maintains that as CCRs determine throughput and inventory in the system, they should be fully utilized and must have large batch sizes in order to reduce setup times. On the contrary, non-CCR excess capacity can be employed for setting up the resource, and thus permit small process and transfer batches. As a result, *variable batch sizes* should be employed in the scheduling process.

2- Taking into account resource finite capacity: in the schedule generation and inventory control, resource finite capacity must be taken into account. For example, the full capacity utilization of a resource that feeds a CCR will lead to a continual increase of WIP in front of the constraint. Decisions concerning the release of material into the shop floor should be taken evaluating the capacity limitations of all the resources of the system.

3- Setting the production priorities: priorities as to which jobs should be run before others and batch sizes determination, should be set analysing the system as a whole and taking into account the constraining capacity of certain resources. Furthermore, production capacities and priorities must be simultaneously set. Priorities are not predetermined, but are dynamic quantities which are continuously calculated during the schedule creation.

### 9.2.2 - OPT scheduling procedure

OPT's procedure for scheduling the manufacturing operations is based on the DBR technique and stresses the role CCRs have in the system ("constraint/bottleneck management"). The scheduling procedure is formed by the first three steps of TOC's 5 focusing steps generic problem solving methodology (Fox 1982, 1985; Jacobs 1983; Ronen and Starr 1990; Wheatley 1989):

1- Identification of the system constraint(s): initially, a load profile and each resource average utilization information is extracted from product demand so that the CCRs of the system can be identified.

2 a) Constraint optimum schedule creation (constraints exploitation): the schedule of the CCR schedule takes the name of "Master Schedule" and is produced by a secret mathematical algorithm. This algorithm schedules all the constraints simultaneously (to avoid suboptimization) and forward in time by taking into account their finite capacity. Priorities (production sequence) and quantities are primarily determined based on customer due dates. However, whenever the four complicating conditions occur (Goldratt and Fox, 1986), OPT determines the optimum sequence based on internal parameters that define the behaviour of the plant.

OPT, after weighting the various factors (i.e. due dates, CCRs capacity, and internal parameters), produces the best answer in terms of: production priorities, production quantities, operation dates, and process and transfer batch sizes. The Master Schedule will ideally allocate all available time at the constraints to set up and operating tasks, in order to achieve maximum production. On the other hand, non-CCRs process and transfer batches will be kept to a minimum to achieve a fast and smooth production flow.

In addition, OPT provides special features that allow consider many realistic scheduling situations (Jacobs, 1983): safety stocks can be located anywhere in the production process, different operation setup times can be modelled, and alternative resources can be substituted at different production rates.

2 b) Master Schedule protection: OPT, following DBR Drum protection measures, locates time buffers in front of the CCRs, assembly points and shipping operations.

3- Subordination of the rest of the plant to the Master Schedule: once the Master Schedule has been obtained, non-constraint resources are scheduled so that they provide the required items at the required moment to avoid starvation at the critical parts of the system (CCRs, assembly, and shipping) and at the same time maintain WIP to a minimum. The procedure employed to create Non-CCR schedules is:

A) Constraint succeeding operations are finitely scheduled forward from the dates defined in the Master Schedule. In reality, this scheduling process is a mix between finite and infinite capacity consideration: it is finite because it takes into account operation process times. On the other hand, it can also be considered infinite because it does not create the schedules taking into account previous operation completion times (it sequences the operations at each resource one after the other assuming that the parts will be available when one operation has finished and the next one starts).

B) Process and transfer batches passing through the non-constraints have different size (batch overlapping), and both are set as small as possible (increased number of setups). This would allow, on one hand, a smooth and continuous production flow; and on the other hand, reduce WIP and lead time.

C) If an assembly operation takes place downstream the CCRs, its schedule is dictated by the availability of scarce parts coming from the constraints.

D) The resources that precede the CCR, assembly, and shipping are scheduled backwards from the schedules of the critical parts assuming they have infinite capacity. In addition, the excess capacity of the non-constraint resources is employed to increase the number of set ups (reduce batch sizes) and protect the system from production disturbances ("catch up" possibility when disruptions take place).

E) Finally, materials are released to the plant in the order determined by the Master Schedule and assuming they reach the critical parts position the "time buffer" amount of time before they are needed. Releasing them earlier would only increase WIP inventory and difficult production control. Moreover, non-constraints are scheduled allowing certain idle time between the operations to absorb the uncertainty inherent to all manufacturing systems.

### 9.2.3 - OPT software structure

Many published papers explain the different OPT modules (e.g. Fox 1982; Fry et.al. 1992; Jacobs 1984; Johnson 1990; Jones and Roberts 1990; Meleton 1986; Ronen and Starr 1990; Tranfield 1991; Wheatley 1989). Briefly, OPT software structure can be divided into the following parts (see Figure 9.1):

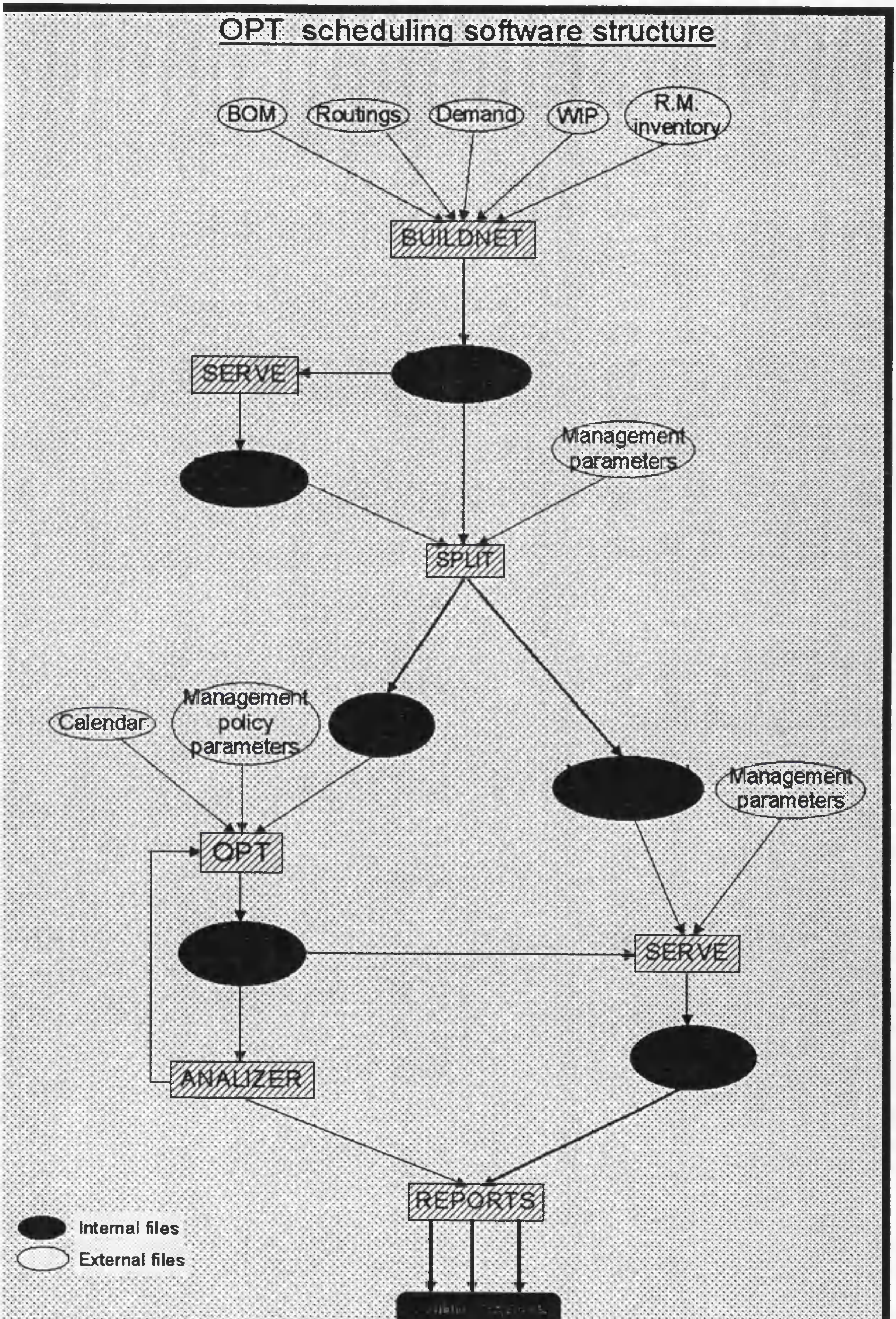



**Figure 9.1:** OPT scheduling software structure

1- Create the shop floor model: the initial task is the collection of all the shop floor data and the building of the factory model. OPT normally extracts the required information from current MRP/MRP-II systems and combines it in a single file called "Engineering Network". BUILDNET is the module that generates this file from five major input files: bill of materials (BOM), product routings, market requirements (sales forecast and firm orders), WIP, and raw materials inventory. As a result, the Engineering Network divides all the data in two sections: product/process network and resource information.

2- Identify the CCR(s): once the Engineering Network internal file has been created, the SERVE module generates a load profile for each resource by scheduling backward from final product due dates and assuming infinite capacity at all the operations. The resources whose load exceed its capacity are identified as critical resources or bottlenecks.

3- Divide the engineering network: when the CCRs are identified, the SPLIT module separates the Engineering Network file into two different parts:

A) The critical net file: contains all the CCRs and all materials and resources that are fed by them. It also includes all end items that require output from any CCR.

B) The non-critical net file: includes all other non-CCR resources, materials, and end items.

The input files of the SERVE module are: Engineering Network, resources load results, and the management parameters.

4- Schedule the critical network: after SPLIT has separated the Engineering Network into two parts, the critical network part is scheduled using the OPT module (the "brain" of the OPT software and secret mathematical algorithm). Its input files -apart from the critical net file- are the calendar file (supplied by management and that contains the available hours per day and the scheduling horizon), and the management parameters file.

The OPT module schedules the critical part forward in time taking into account resource finite capacity. The output produced by this module is: process and transfer batches size, priorities, net requirements, and size of the buffer to be placed before the critical points.

5- Schedule the non-critical network: the SERVE module is used again to schedule the non-critical part of the network based on the schedule created by the OPT algorithm. This module is similar to MRP in a sense that: (a) it schedules the work backwards in time from the Master Schedule, (b) it time phases each production stage using component lead times, (c) it assumes infinite capacity, and (d) it generates purchased and production orders.

6- Data analysis and output files presentation: the ANALIZER module provides the scheduler with detailed data related to the Master Schedule so that adequate changes can be made in the initial input data or in the management parameters (and run OPT again).

Finally, the REPORTS module, employing the data generated by the ANALIZER and the non-CCR schedules, produces output reports that include: resource utilization levels, scheduling information, material requirements forecast, raw material expeditor report, WIP information, due-date performance report, etc..

### 9.2.4 - Management parameters

The managerial parameters contain the scheduling fundamentals based on TOC ideas (i.e. DBR, 5 focusing steps, and 9 scheduling rules). They are utilized to (a) illustrate particular shop floor management policies and (b) describe the nature of the plant. OPT's management parameters are (Goldratt 1980):

■ Minimum Machine Time (MMT): this parameter describes the level of control that the plant exercises on the movement of parts and workers. It defines the transfer batch at each operation so that the time spent at the operation on the transfer batch will be greater than the MMT. For example, if the MMT is set 300 minutes and the unit process time is 30 minutes, the transfer batch for the operation will be 10 units.

■ Desired Stock (DS): it dictates the level of safety stock the plant wants to keep in the production process to achieve a smooth flow and protect the system from production disturbances. This parameter is a number which determines the buffer size for each operation by multiplying it with the transfer batch of the succeeding operation. For example, if the operation transfer batch is 10 and DS is set 3, then the buffer size of the previous operation will be 30. The schedule will determine if and when the buffer should be filled.

■ Flow Parameter (FLOW): is a correction of the MMT parameter and determines the smoothness of the flow of parts through the plant. The MMT applied by itself would cause a jam at every fast operation (at fast operations, large quantities of parts would be needed in order to work for a single MMT period). Thus, the FLOW parameter trims the large transfer batches required at the fast operations by multiplying its value with the MMT of the preceding operations. For example, if FLOW is set 4 and the MMT at any operation upstream the fast operation is 30, at any successor operation the transfer batch cannot exceed 4*30=120.

■ Maximum Batch Limitation (MBL): this parameter is a correction of the MMT and DS and it is only applied at the initial stages of production where there is the possibility of producing quantities too large to be absorbed by the resources in the reasonable future. Transfer batches or buffer sizes will be trimmed if they are larger than the amount needed for overall production in a specific period of time.

### 9.2.5 - OPT scheduling assumptions

According to Jones and Roberts (1990), OPT makes the following assumptions about the CCRs (referred as bottlenecks) and the schedules:

1- There is a limited number of bottlenecks in the system (less than five in most plants).

2- Bottleneck operations will remain stable from one production period to the next and within the scheduling time bucket. Goldratt (1981) maintains that the "wandering bottlenecks" phenomena occurs as a function of poor scheduling or in the cases where the capacity of the system is close to balance. Therefore, for bottlenecks to remain stable, at least (a) demand should be statistically stable and (b) the plant should not be balanced.

3- Bottlenecks need to be forward loaded to 100% of their capacity.

4- The schedule rigidity imposes that the users must strictly adhere to it (it is assumed that employees will follow the schedule and that the employers can follow the schedule).

Fox (1982) affirms that a successful OPT implementation requires that (1) the realities of manufacturing can be modelled, and (b) the environment is appropriate (i.e. traditional cost accounting systems -that are an enemy of productivity- are supplanted by TOC concepts).

## 9.3 - OPT implementation

OPT scheduling software implementation requires a total change in the established production management policies and personnel attitudes. Former production measurement systems, shop floor practices, and employees bearing will suffer a radical change with the introduction of OPT and the application of the TOC concepts. Such a drastic organisational change can only be achieved with the total corporate commitment and after an extensive educational process.

The common implementation stages and the activities the company has to undertake in order to successfully implement OPT are (Johnson 1990; Jones and Roberts 1990):

1- Project definition and planning: the implementation of OPT begins with the definition of the target area in which install the package, measuring the size of the task (e.g. number of product families, resources, people, etc..), and determining intermediate activities and objectives (timescales).

2 - Project execution: the final objective of OPT installation is to build a system that will produce valid schedules and create an environment that will make the most of them. The following implementation activities have to be carried out:

a) OPT team environment preparation: project team establishment, team education, and hardware and software configuration.

b) Plant analysis: business objectives and the particular production management policies definition.

c) Model building: the manufacturing environment is modelled by extracting data by interfacing OPT with current information systems, building the Engineering Network, and validating and tuning the model.

d) Initial schedule adjusting: the first schedules are created from the loaded data to adjust the input information and the management parameters.

e) Thorough internal education: education sessions concerning OPT principles (TOC, DBR, Buffers, role of CCRs, etc..) are organized at all company levels.

f) Schedule launching and monitoring: initial schedules are launched to the shop floor and their performance monitored to carry out the required adjustments.

g) Production system setup: the schedule creation is automatized, management and control systems are adjusted, and the required administrative procedures changed.

In practice, OPT implementation has no true beginning or end since it is a system for continuous improvement of the manufacturing process. There is, however, a period in which production operations undergo extensive changes (i.e. personnel learn and adopt OPT principles, and initial schedules are created). The time scale for these changes varies between organisations. However, it normally takes five/six months until the first schedule can be launched.

## 9.4 - Evaluation of OPT

### 9.4.1 - OPT location in a general framework of scheduling softwares

A complete classification of current scheduling softwares has been performed by Harrison (1991a, 1991b, 1993a, 1993b). He is the director of an independent consultancy specialist in scheduling systems and maintains that most of the scheduling softwares fall into one of the following four broad categories:

1 - Post MRP, Works Order Schedulers: these packages deal primarily with the orders created by MRP/MRP-II, and are targeted at assembly plants that produce the items in discrete batch sizes.

The softwares concentrate on sequencing the queues of work at each resource in order to get the best due date performance and meet the assembly schedule. As they have no concept of finished products stock (they simply recognize the manufacturing order as the demand) and they do not have links with related component orders, there is no form of synchronising the operations (a delay on a key part cannot be automatically communicated to the other parts and resources). As a consequence, WIP will tend to accumulate and production control results a difficult task.

There are two types of Works Order Schedulers:

a) Computerized Planning Boards: these systems are simply electronic planning boards that effectively replace the manual planning boards often employed to schedule and control production. The manufacturing orders received from MRP are displayed as a series of coloured Gantt Chart blocks that consume capacity (represented by time across the screen).

The software allows the scheduler to reallocate the orders in a variety of ways but it does not attempt to optimise the sequence. Usually automatic scheduling is limited to simple due date sequencing. Furthermore, normally only resource capacity is taken into account and neither labour nor tools are considered.

However the power of these packages is that they enable the visual replanning of the board very quickly (when a breakdown occur or an urgent order has to be included in the schedule, the scheduler can make the changes on the board and automatically see the damage created on the other orders).

b) Optimising Works Order Schedulers: they are similar to the above, but in this case the software uses algorithms (heuristic rules) to sequence the orders at the resources in order to minimise set up time and achieve a good due date performance.

The strength of these packages is that they often include special rules that can be developed to reflect the optimisation techniques employed at a particular plant or group of resources. As such, they can also be referred as "Rule-Based Planning" systems. They are useful for the effective control and scheduling of semi-process industries (repetitive batch situations), where the specialised nature of the process is unlikely to be able to follow a schedule generated by standard algorithms. Applications of Optimising Works Order Schedulers include typical "A" plants (e.g. multi-station gravure printing presses).

2- 'Rate of Use' Schedulers: these softwares are primarily aimed at continuous processes or semi-process industries (e.g. food, drink, and pharmaceuticals) characterized by: (a) make-to-stock situation, (b) distribution type environment, and (c) with the main objective of maximizing customer service through a maximum utilization of the dedicated resources and minimum set up times.

These softwares do not necessarily utilize manufacturing orders, but allow the processing of materials at a "rate of use", producing the products at each resource also at a "rate of use". This permits the next operation start processing as soon as the first product is available, enabling directly linked operations to be handled.

3- Structured Schedulers: OPT is the originator of this type of scheduling systems. They are designed to schedule the manufacturing operations in a synchronised manner (as such, they contain knowledge of the Bill of Materials structure of the products). CCRs are identified and the sequence of jobs in them optimized in order to answer demand in the best possible manner. Batch sizes are set according to the need for flow and synchronization between operations. Non-CCRs on the other hand, are scheduled to match the CCRs optimum schedules.

In this case, the software replaces the MRP/MRP-II system by producing the net requirements for purchase and manufacture components, and determining the batch sizes to ensure a smooth production flow. They use forward finite scheduling, but also employ backward scheduling to define priorities and create the initial synchronisation.

### 9.4.2 - OPT software applicability

### 9.4.2.1 - OPT software users

Jones and Roberts (1990) present a list provided by the OPT vendor (STG) in which OPT users are drawn from the US, UK, France, West Germany, Holland, Denmark, Australia, Norway and Sweden. By mid 1984, 22 of the hundred largest 'Fortune-500' companies had implemented OPT in some part of their operations, with names like Eastman Kodak, General Electric, General Motors, STC, Ferranti, British Steel, and British Aerospace among the OPT users.

A survey carried out by White and Wharton (1990) about the manufacturing approaches employed in New England (US) revealed that only 1.7% of the companies were using OPT (with 4.3% of them working toward it).

In another more recent survey performed in UK about the shop floor scheduling practice (Little and Jarvis 1993), from the 35 properly completed questionnaires, 9% of the companies (about 3-4) were currently using OPT.

Finally, the more illustrative survey is the one accomplished by Fry et.al. (1992) in 1989. From the 60 US OPT users they contacted, only 22 completed the survey, with, 4 of them currently implementing the software, 15 using it, and 3 no longer utilizing the software. The type of industry and the production orientation of the companies were as follows:

| Industry | Number | % |
|---|---|---|
| Automotive | 11 | 41 |
| Aerospace | 5 | 19 |
| Textiles | 3 | 11 |
| Other | 8 | 29 |

| Production orientation | Number | % |
|---|---|---|
| Make-to-order | 28 | 64 |
| Make-to-stock | 9 | 20 |
| Make-to-stock and Assembly-to-order | 5 | 11 |
| Other | 2 | 5 |

Based on these results, the automotive industry and the companies oriented toward make-to-order production are the principal OPT software users. Jones and Roberts (1990) also corroborate these results with the automotive industry as a major OPT user (28%).

#### 9.4.2.2 - OPT software implementation case studies

Appendix C includes the case studies of successful and unsuccessful OPT implementations extracted from published papers and personal contacts. The following drawbacks and benefits can be drawn from the OPT installation experiences.

+ <u>Major OPT drawbacks</u>

- Initial data gathering problems.
- High data accuracy required for the CCR.
- Not user friendly.
- Long learning period required.
- It requires appraise and rigorous train at all levels.
- Long schedule generation times in some cases (up to 9 hours).
- Operators have to obey OPT schedules.
- Company wide acceptance and commitment are indispensable.
- Certain production scheduling situations cannot be fully represented.
- Dynamic changes in the CCRs are difficult to handle.

+ <u>Major OPT benefits</u>

- High overall inventory reductions (up to 60%).
- Increased throughput (up to 60%).
- Increased inventory turns.
- Reduction in material shortages and delays of critical parts.
- High production lead time reductions (sometimes more than 50%).
- Due date performance improvement.
- Improved customer service.
- Improved products quality due to the achievement of a low inventory environment in which problems can be better spotted and corrected.
- Warehousing space freed up (in some cases).

Other OPT strong points include:

- Useful as a long term planning tool (simulation capabilities).
- Powerful report capabilities that can improve internal communication.
- Investment payback -sometimes- in between 3-6 months.

#### 9.4.2.3 - OPT and the manufacturing systems

The variety of the manufacturing environments and the diversity of the scheduling problems form such a wide domain (see chapter 2) that no single production scheduling technique or scheduling package would be capable of answering to all the situations. The appropriateness of a scheduling software for certain production systems will be mainly determined by (1) its modelling capabilities (it should be capable of incorporating the static and dynamic parts of the system) and (2) the planning capabilities (it should reflect management decisions under different manufacturing circumstances). With these two aspects in mind, OPT will be more suitable for some manufacturing systems that others.

+ <u>Suitable production environments</u>

In section 8.3.2.1 was pointed out that certain production line situations and general batch cases were the most suitable environments for the DBR application. Similarly, OPT suitability for some production environments (supported by different authors) is:

» Repetitive production line situations characterized by: (a) stable production demand in which the CCRs do not "wander" through the plant and can be easily identified (unbalanced cases), (b) reduced number of production routes or viable process plans that lead to a simple static structure (so that OPT can adequately model the system), and (c) predictable process times (machine dominated) to permit high schedule adherence. Some of the authors that confirm this fact are:

1) Jones and Roberts (1990)> repetitive manufacturing situations with stable bottlenecks.

2) Jacobs (1983)> High volume, large batch-size operations with few key products or few individual production operations.

3) Roberts (1987)> companies with long manufacturing lead times and heavy investment in inventories.

4) Frizelle (1989), Fry et.al. (1992), and Jones and Roberts (1990)> assembly operations (automotive industry)

» Large batch operations (Bylinsky 1983). However, unstable and very complex production environments may cause problems to the optimal schedule generation and the accurate modelling of specific production cases (see last two case studies of Appendix C).

+ Unsuitable production environments

Deduced from the above, complex manufacturing systems (a) containing many process plans (e.g. job shops), (b) poorly defined production routes (e.g. project), or (c) highly man oriented -unpredictable process times- (e.g. project and job shops), will require too much structure for OPT to build the models. Furthermore, the large number of potential schedules (based on unstable demand, and therefore, unstable bottlenecks) will make OPT an inappropriate instrument to cope with the inherent variety of those environments.

In addition, high volume, balanced repetitive production lines and continuous process industries do not have a crearly defined constraint and other techniques rather than OPT would bring major benefits.

+ V, A and T plants

» V plants are typical process manufacturing plants that operate in a batch fashion (see section 6.6.6). In these cases, there is often a single CCR in one of the common initial process stages that affects a wide proportion of products and the material is largely common with well defined process routes. Scheduling is normally focused on exploiting the CCR of the system and subordinating the rest of the plant to it. Therefore, OPT can bring enormous benefits for this type of plants (Frizelle 1989, Harrison 1993b, Johnson 1990).

» A plants are the opposite to V plants. They contain a huge variety of different production processes and complex manufacturing situations. In the cases where demand is unstable and CCRs move from one part of the plant to another, MRP/MRP-II will be more useful than OPT. However, if there is a clearly defined CCR, overall system synchronisation will be possible to achieve with the OPT software (Harrison 1993b, Johnson 1990).

» T plants are high volume assembly plants that make a range of similar products from many common components. Synchronisation between component production processes and assembly is the key to effectively manage and control the whole plant (material "stealing" in the assembly operation has to be eliminated). OPT "..will be imperative in order to achieve synchronisation" (Harrison 1993b).

### 9.4.3 - OPT's weak and strong points

The following OPT strengths and weaknesses extracted from different authors' work can be added to the users' opinion mentioned in the introduction:

» OPT schedules: according to Fox (1982), OPT produces robust schedules that last "..an average of two weeks -an incredible performance based on the users experiences with other systems-". Furthermore, schedule generation process is very quick due to the method employed in structuring the data (Fox, 1985; Goldratt, 1988). Wheatley (1989) maintains that although run times are a function of computer size and network size, run times of under 25% of the time it takes to run MRP for the same situation on the same computer are the norm.

In addition, OPT has a holistic vision of the system by producing the best possible schedules for the identified constraints and subordinating the rest of the system to them ("local optima do not add up to the optimum of the whole" -Goldratt and Fox 1986-).

On the contrary, Fry et.al. (1992) maintain that OPT is sometimes considered as a "black box" (the output is straightforwardly produced from the introduced inputs) that creates counter-intuitive schedules. Moreover, the schedules created are tight and must be followed in detail (Jones and Roberts 1990). Frizelle (1989) also asserts that OPT "..has a ruthless way of exposing the real problems. An inexperienced analyst implementing the software can bring a plant to a virtual halt when he first issues schedules. As the schedule only makes what is needed, a plant full of inventory could find itself with no work". Finally, a high level of discipline is required in the shop floor in following the schedules. There is the fear that any delay in updating the system or in following the schedules will be disastrous (Meleton 1986).

However, Fox (1983) maintains that "A good algorithm is useful, but only on getting the last 10% of the benefits. The power of OPT is in the thought process behind it -the "Thoughtware"- and not in any formula buried in the software". He also recognizes that "..OPT is not an optimum", but although it may be a better solution than the one provided by OPT, its strength lays on the underlying concepts (Fox 1985).

» Simulation capabilities: due to the short computing time required to produce the solutions, OPT software can be used as a simulation ('What if') tool. Long range strategic decisions can be carried out by simply simulating the plant under different conditions.

Related to this, Jacobs (1983) suggests that since the OPT program does not consider costs or profits it should not be used for making long term decisions.

» Data requirements: Goldratt (1982) claims that data accuracy is only required in the small portion of the system where the constraint resource is placed (Goldratt 1982).

Related to this, OPT is subject to the data problems associated to any computer system (Tranfield 1991 -internal paper-): (a) it will be as good as the data provided, (b) accurate day to day -dynamic- data must be maintained, and (c) it can only respond to changes in situation as fast as data is fed to the computer. Additionally, the claimed reduced data accuracy requirement is not totally true for those situations of unstable demand or balance capacity environments. In those cases, different product mixes can make the constraint move to different parts, so that the same commitment in the data collection and accuracy is needed everywhere.

Furthermore, Jacobs (1983) asserts that OPT uses a very tight network organization and coincides with Meleton (1986) in the fact that the data needed to model this network from raw material to finished inventory requires considerable work to maintain.

» Implementation process: some OPT users had the payback of the investment in the package and of the implementation process -pointed out in section 9.3- only in 3-4 months. However, OPT software implementation requires -apart from a thorough data collection and maintenance process- a radical management style change. Frizelle (1989) declares that the major drawback of the OPT software is the "..heavy burden implementation put on management". The extensive education and training required at all corporate levels and the change of attitude can only be carried out if there is a real faith in the OPT software and its underlying TOC philosophy.

» Production environments: OPT is claimed to be capable of realistically represent system capacity and constraints, and of modelling a wide variety of plant types (Goldratt 1980): assembly lines, electronic assembly plants, metal job shops, and NC batteries. In addition, it incorporates the production behaviour and management style in the management parameters input file.

However, according to Jacobs (1983), OPT scheduling procedure has shown to be very sensitive to these parameters, and special attention should be paid to their proper setting and adjusting. Moreover, in section 9.4.2.3 was exposed that the most suitable environments for OPT to be implemented are repetitive production lines and large batch operations. Finally, due to the individual characteristics of the production environments and the proprietary/standard nature of the software, particular situations (e.g. multiple and shifting bottlenecks) cannot be incorporated and even simple suggested modifications to the software are difficult (Morton and Pentico 1993).

### 9.4.4 - Last comments

OPT software contains a "clever" scheduling procedure that embraces the concepts of a powerful production management philosophy and that has brought amazing results for most of the companies that have implemented it. However, there are a few remarks that should be made about the package.

» Exaggerated initial claims. According to OPT's initial vendors, the decision to buy OPT was a choice for survival in the 1980s and the vehicle to rise US economy against the Japanese "victory" with JIT (Fox 1983). OPT was presented as a combination of MRP push and JIT pull logic and an enhancement of both philosophies (Jones and Roberts 1990). Contrasted to these claims, there are the failed OPT implementation cases and the users negative comments mentioned in previous sections. Further, OPT seems to be only applicable in repetitive manufacturing situations, assembly industries, and certain batch environments.

» Astonishing results. Most of the companies that have adopted OPT have reported extraordinary results. These results cannot be ignored, however, considering the high price a company has to pay to buy OPT (the current price of OPT21 is around £100000-£200000) and the effort required for its implementation, who would dare reporting poor results?. In addition, company image would be damaged if negative results are made public and direct competitors would gain relative advantage from that.

» POOGI stoppage risk. The OPT software, with the aid of a secret -and sometimes counter-intuitive- algorithm, produces detailed scheduling solutions from the introduced inputs. The user cannot command the scheduling process ("black box" system), and once the schedules are produced, they have to be strictly followed in the shop floor. This 'blind' rely on OPT's optimal solution can produce a growing lack of interest in the scheduling task and 'relax' the managers and employees from seeking the final TOC objective: the POOGI.

# 10 - DISASTER SCHEDULING SOFTWARE

## 10.1 - Introduction

DISASTER software was created by a group led by Goldratt in the late 1980s as an enhancement to OPT. It is -like OPT- based on the Drum-Buffer-Rope scheduling technique and embraces similar assumptions. However, DISASTER's creators seek the construction of an information system based on the TOC ideas that would be able to provide the managers immediate and accurate information about different matters related mainly to the management and control of the organisation.

The goal of DISASTER's originators is ambitious, but so far, they have produced one of the three phases -they maintain- an information system should have: the scheduling phase.

### 10.1.1 - DISASTER as an information system

Most of the theoretical analysis and underlying principles of DISASTER are included in Goldratt's "The Haystack Syndrome" book (1990b).

According to Goldratt (1990b), an information system should be capable of providing the decision makers -managers- the precise information so that they can answer precisely the questions that they encounter. Some of the managerial question can be: should this particular order be accepted?, what offer should be tendered for this customer specification?, should the request for more machines be accepted?, what can be done to reduce lead times in product design?, how can the performance of a local area be evaluated?, which supplier should we choose?, should this part be made in-house or should it be brought from outside?, etc..

+ Data systems vs information systems

The above questions can only be answered if the manager possesses the adequate information related to the subject. Therefore, information is defined as (Goldratt 1990b) "the answer to the questions asked".

In contrast to this, there is the concept of data. Data is defined as (Goldratt 1990b) "every string of characters that describes anything about reality" (e.g. supplier addresses, product designs, warehouse contents, quality of products, etc..). As a result, the required information is not readily available, but must be deduced from the elements of data contained in the organisation.

The above lead to recognise the existence of two different systems:

1- Data systems: a system that supplies readily available information.

2- Information system: a system that extracts and represents data in some appropriate form for the user (a system that turns data into information).

+ TOC's 5 focusing steps: the approach to process the data

TOC maintains that appropriate information can only be achieved through the 5 focusing steps generic decision process. This approach enables ascention of the information ladder from basic data through various levels, until the required information is achieved. This being so, it will allow identification of the system constraints from the available data, deduce tactical answers, and obtain the pursued information.

### 9.1.2 - Architecture of an information system

A comprehensive information system must have a hierarchical structure (Goldratt 1990b): what is required data to one level is transformed into information to the upper level guided by the generic decision process. Moreover, the data system must be centralised so that all the areas of the organisation can gather the basic data and extract the information from it. Accordingly, the information system should be decentralised and should be fed from the single data bank.

The levels of the hierarchically structured information system would be (see Figure 10.1):

1- The SCHEDULE stage. In order to be able to even start answering the managerial questions the required data should be generated. Following the 5 focusing steps decision process, the most fundamental element is the identification of the system constraints. To do this, there is no other choice but to schedule the operations of the company. Thus, the SCHEDULE stage is the most basic stage of the information system.

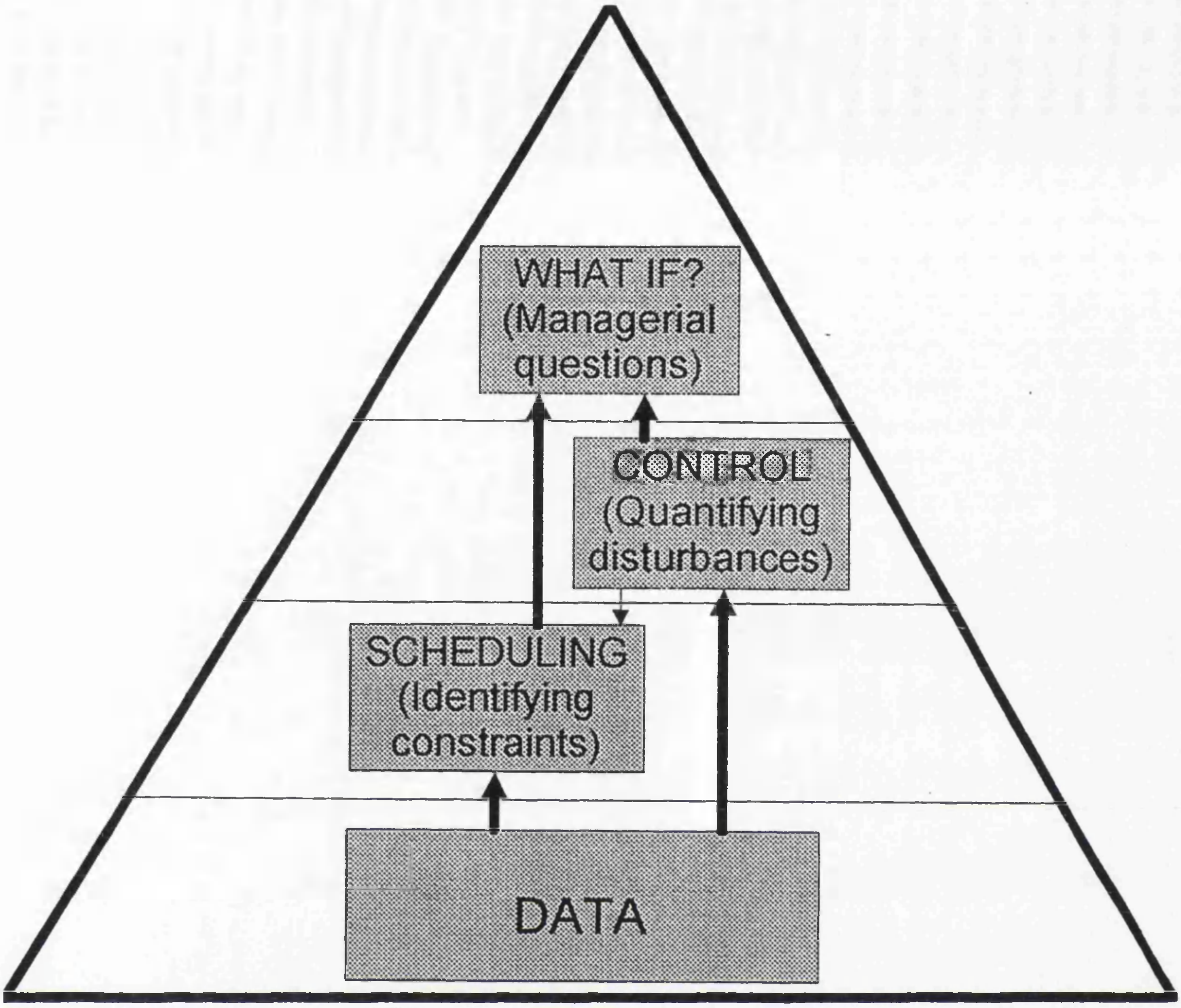



**Figure 10.1**: architecture of an information system (source: Goldratt -1990b-)

2- The CONTROL stage. The CONTROL stage is located on top of the SCHEDULE stage and it has the ability to quantify the level of production disturbances (Murphy) in the system. At this stage, deviations from the schedule should be assessed in order to determine the magnitude of inventory and excess capacity -at the non-CCRs- required to handle production disturbances, and be able to answer, quite reliably, any WHAT IF questions (e.g. where to focus the efforts to reduce Murphy and improve processing).

The CONTROL block cannot be used before the SCHEDULE block is operational (since one of its functions is to know where things are versus where they should have been). However, the schedules should contemplate the existence of disturbances in the production process. A predetermined estimation of their magnitude is required at the SCHEDULE stage in order to define the Time Buffers and the necessary level of protective capacity -excess capacity- (estimates that will be refined latter at the CONTROL stage).

3- WHAT IF stage. Only when the SCHEDULE and CONTROL stages are operational, the information system ultimate goal can be reached: the ability to answer the managerial questions contained in the WHAT IF stage. This stage is at the top of the information pyramid and will be focused on elevating constraints or preventing their creation.

### 10.1.3 - DISASTER's capabilities and claims

DISASTER will be released in three phases; each phase mirroring the stages that conform the information system architecture just reviewed. According to its vendors, the goal of DISASTER is (AGI DISASTER's manuals 1990): "answer any business question that any manager in the "Throughput World" might pose to it -any question". DISASTER's scope ranges from scheduling the shop floor to the strategic future of the organisation. Furthermore, "DISASTER is only limited by the ability of its users to ask the right questions".

The first phase of DISASTER (scheduling) is a software tool intended to support Drum-Buffer-Rope in companies implementing TOC. It is claimed that it has the ability to perform massive numbers of computations at lighting fast speeds and, as a result, it "has taken DBR scheduling leaps and bounds beyond what could be done manually in a company" (AGI DISASTER's manuals 1990). It can also "generate a schedule that is extremely 'immune' to fluctuations on the shop floor, and which remains valid long after its release". But the biggest contribution is its ability to simulate the schedules: predict future conflicts with demand so that constraint resources can be detected and realistic schedules can be released to the shop floor.

### 10.1.4 - DISASTER's fundamentals

The fundamentals of DISASTER are:

1- The scheduling process is based on an *iterative* application of the DBR approach. Initially, the constraint resource is identified, exploited to its fullest, and the rest of the system subordinated to it. Then, non-constraints are subordinated and the conflicts that arise between the CCR and the non-CCRs uncovered. If new constraints are identified, the exploitation process starts again. These iterations continue until all conflicts are identified and resolved.

2- As the constraints are sequentially identified and optimized, overall optimization measures like, for example, variable process and transfer batch size determination in order to achieve a smooth production flow would not be possible to apply.

3- The user takes an active part in the scheduling process by determining scheduling solutions (e.g. allocating overtime, offloading parts from one resource to another, defining buffers, splitting batches, changing orders due dates, etc.) and commanding the scheduling course (e.g. identifying constraints, subordinating and defining new constraints, ignoring the proposed solutions and adopting particular ones, etc.). The user *interacts* with the software.

4- Finite resource capacity is taken into account while developing the schedule.

5- In order for the final schedule to be feasible, all individual constraint schedules cannot be in conflict with each other.

### 10.1.5 - DISASTER's assumptions

The principal assumptions made by DISASTER are:

1- Limited number of constraints. Only a very small number of constraints should exist in the plant; otherwise, it would collapse (AGI DISASTER manual 1990). This is in accordance with the first of the basic fundamentals stated above: DISASTER will be considered a practical tool as long as the number of iterations are limited, so that a solution can be found in a fairly short time.

2- Link between the environment and DISASTER. The environment in which DISASTER is installed must adhere to the elements of the software, as well as to the principles of its underlying philosophy. DISASTER is defined as a tool targeted at companies which are immersed in the "Throughput World" or are moving in that direction. DISASTER would only be released to the market under the condition that the organisation undertakes an education process with the purchase of the package.

3- There are no policy constraints in the system. DISASTER does not include in the software the possibility of incorporating any management policy which may exist on the shop floor. Its creators maintain that if the schedule cannot be followed on the shop floor is due to the existence of a policy that prohibits the system from producing the most throughput possible. Such "policy constraint" should be broken according to the principles of the "Throughput World".

4- inaccurate data: DISASTER assumes that the data "is absolutely lousy..comprised of best estimates, and that it is all prone to statistical fluctuations" (AGI DISASTER manual 1990).

5- Production disturbances do exist in the system: production disturbances disrupt the normal production flow and have to be properly handled to avoid throughput losses or unnecessary increase in inventory. Buffers located in strategic places are designed to lessen the negative effects of production disturbances and compensate for the possible limitations in modelling the production environment (AGI DISASTER manual).

### 10.1.6 - Why is it called DISASTER?

The reason a scheduling software is given such a name comes from the above assumptions. If the environment in which DISASTER is going to be installed does not have the ability to identify and break policy constraints, the schedules produced "will cause huge problems in the plant...and result in: chaos and mutiny" (AGI DISASTER manual 1990).

When DISASTER is implemented without undergoing the cultural change required to support the assumptions of the software, the benefits DISASTER can bring will probably turn into drawbacks. DISASTER is very much like a scalpel. "If used as their creators intended, they are two of the most incredibly important and beneficial tools available today. However, if used without the knowledge and skills necessary to control the power of these tools, their use can lead to disasters" (AGI DISASTER manual 1990).

## 10.2 - DISASTER's structure

+ The system

DISASTER's software is designed to run on an IBM or compatible personal computer with a minimum requisite of a 386SX chip, colour monitor, and about 4Mb of RAM. Moreover, in order to achieve high computer speeds, all the data must reside in memory and the capacity of the computer processor cannot be shared with other applications.

+ The programs

DISASTER is formed of three main programs (see Figure 10.2):

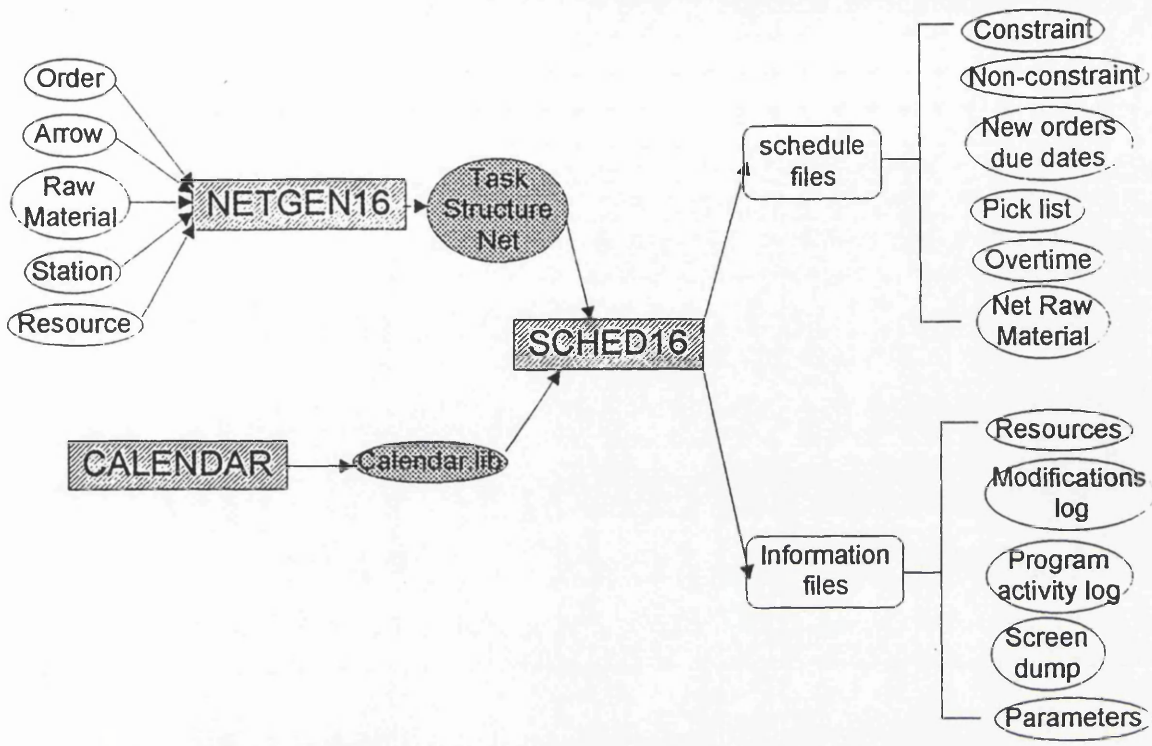



**Figure 10.2**: DISASTER's programs

1- NETGEN16. This program gathers all the data needed for the scheduling stage (data from which information will be obtained at the 'What If?' phase), and transforms it in an internal file called "Task Structure Net" that is held in the on-line memory of the computer.

The inputs to NETGEN define the different characteristics of the products and the plant that are taken from a set of text files which can be created manually or extracted from the current production control system (e.g. MRP). The required external files are:

» Order file: defines the final products that must be produced together with quantities and due dates.

» Arrow file: describes the path for producing a product from raw material, through process stations, to the final product. In addition, scrap percentages and time buffers can be defined at each process stage. Arrows point material in the direction of its flow, specifying the station "From" the material flows and the station "To" the material flow. Stations can be raw material or resources (process stations) but never a final product (final products are the ones included in the order file).

» Raw Material file: contains the list of all the raw materials required to fulfil the demand. The quantity of stock on hand and the delivery time are also included.

» Station file: contains the resources a part must pass through from raw material to final product. It includes the description of each operation, in terms of the process station name, resource required, process time, set up time, and WIP.

» Resource file: describes the resources used at the stations file and the number of identical resources available.

2- CALENDAR. This program is used to create calendars which tell the schedules creation module how many hours the resources in the plant work each day within a period of time. Two types of calendars can be defined in DISASTER: (1) the "Default" calendar that is used for all the resources of the plant, or (2) the "resources specific calendar" that will be operational instead of the Default calendar for the resources that define it in the resources input file.

3- SCHED16. Is the program of DISASTER that produces the schedules based on the Drum-Buffer-Rope scheduling technique. The scheduling process and the modules comprised in it (see Figure 10.3) will be thoroughly reviewed in the next section.

The output files are only obtained after the program has successfully completed the scheduling process and acceptable schedules -without conflicts- have been produced. These outputs -as the inputs- take the form of text files which may be represented in a more adequate form with the aid of an external software. They can be grouped into:

■ Schedule files: (a) schedule for the stations of each constraint resource, (b) non-constraint schedule (it must be noticed that only the gating operations and those using common parts are contemplated here; the rest do not need a schedule according to TOC as the operator will process the batches as soon as they arrive), (c) status of the order due dates (some may have changed during the scheduling process), (d) pick list file, (e) overtime assignment file, and (f) net raw material requirements file.

■ Information files: (a) status of each of the resources (division between constraints and non-constraints), (b) modifications made to the initial Project data, (c) Sched 16 program activity logs, (d) screen dump file, and (e) parameters file.

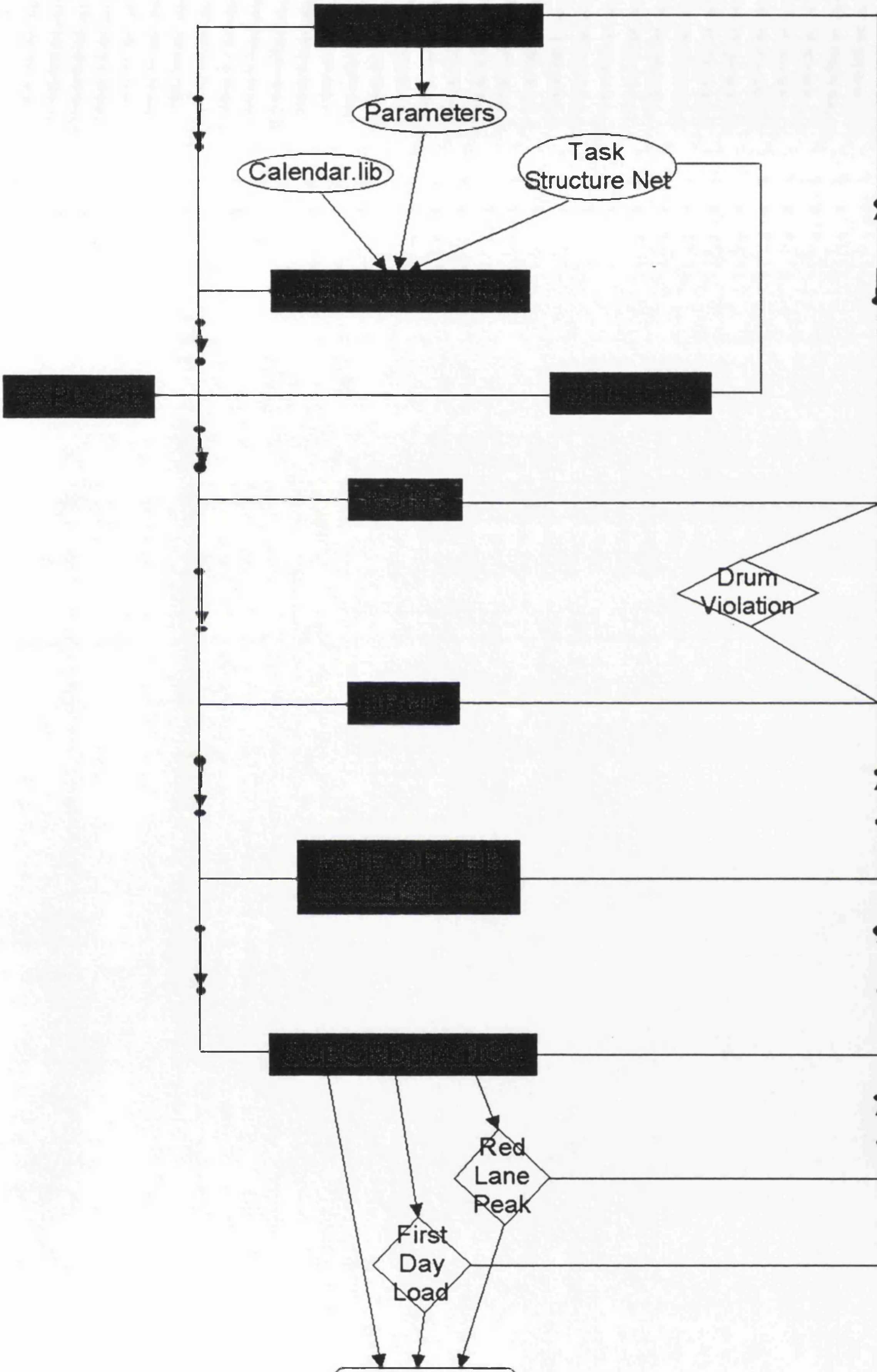



**Figure 10.3**: DISASTER's scheduling modules

## 10.3 - DISASTER's scheduling procedure

The scheduling routine employed by DISASTER is based on the iterative application of the first three steps of the 5 focusing steps generic decision process: (1) constraint identification, (2) exploitation, and (3) subordination. The system will move through these three steps over and over, each time solving, with the aid of the user, the conflicts at the identified constraint and subordinating the rest of the plant to it. This iterative scheduling process will finish when at the end of the subordination stage no more unsolved constraints remain (no violation with reality can be found in the system).

### 10.3.1 - The market the initial constraint

Following the above procedure, initially, the first constraint of the system must be identified. To do so, any resource of the plant can only be identified as a bottleneck or a Capacity Constraint Resource (CCR) after the requirements the market puts on it as a function of time are examined. "We face the situation where, in order to identify such a constraint, first we need the schedule itself" (Goldratt 1990b). Therefore, the market is identified as the initial constraint.

The next step is the exploitation of the identified constraint. This simply means that order due dates are met. In the subordination stage, the rest of the system -the plant itself- works to achieve the above due dates. However, some conflicts with the limited capacity of a particular resource may arise at this stage. Attention should now be paid to the new identified constraint, so that its conflicts are removed and the scheduling process can progress.

### 10.3.2 - Identifying the first resource constraint

To recognise the existence of a constraint and quantify its magnitude, the loads the market places on it must be contrasted with its available capacity. This is done by specifying the scheduling horizon and estimating the work loads for the orders included in this time period. The scheduling horizon is defined by the user by using the PARAMETERS module.

The IDENTIFICATION module of DISASTER then lists all resource load/capacity ratios and suggests the most heavily loaded resource as the constraints. At this stage the user can make three choices:

1) Follow DISASTER's recommendation and pick the most heavily loaded resource as the constraint of the system.

2) Check, by the aid of the EXPLORE module, all the data concerning to the orders and loads, and choose a different resource due to: (1) erroneous data, (2) the new selected resource has a complex set-up situation and has shown to be the constraint, and (3) the user knows that with some easily implemented solutions (e.g. offloading, subcontracting) the suggested constraint can be removed. Even if the user makes a wrong decision here, DISASTER always gives the chance to come back to this stage.

C) All resources have enough capacity to answer the market requirements and the user does not identify any of them as the constraint. DISASTER in this case presents the option of designating the market as the only constraint and creates the output files by subordinating the system to it.

### 10.3.3 - Exploitation of the identified constraint

Assuming that the user has identified a resource as the constraint of the system, he/she is confronted now with (a) delay the delivery of some orders if the identified CCR is a bottleneck or, (b) increase the throughput of the constraint by resolving some of its conflicts and increasing its capacity (overtime, offloading). The latest case represents the exploitation stage and is performed by the RUINS and DRUM modules.

At the exploitation stage the system tries to define the 'ideal' time for each job to be processed on the constraint. To do this, DISASTER uses the concept of "shipping buffer" (it represents the length of time the user defines for the batch to move from the constraint to shipping). Similarly, the user has also to determine in the initial PARAMETERS module -apart from the shipping buffer- the constraint and assembly buffers.

#### 10.3.3.1 - Building the Ruins

Given the due date of the order for the constraint and the shipping buffer, the RUINS module of DISASTER subtracts the shipping buffer from each order due date and places the resultant batch -taking the form of a block- on the time axis. Each batch is scheduled at its ideal time without any capacity consideration. Where two batches must be performed simultaneously, they are shown on top of each other. The final result is the build up of a sort of Gantt Chart (called Ruins) showing how batches should ideally be processed by the constraint (see Figure 10.4 ).

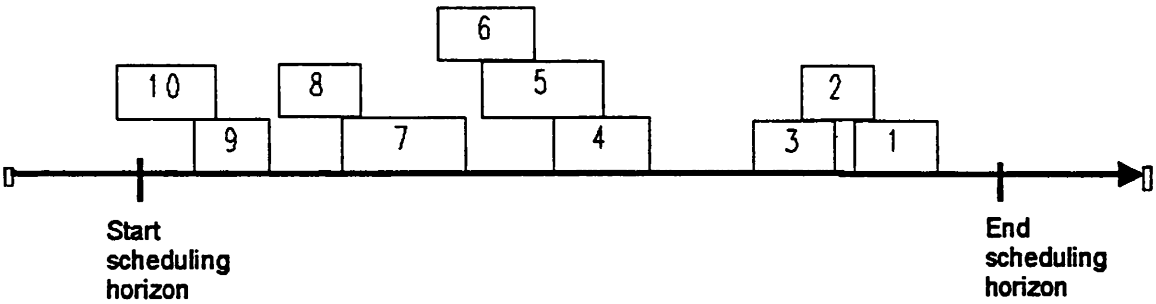



**Figure 10.4**: the ruins

Before progressing with the exploitation analysis, it has to be mentioned that DISASTER gives the possibility at any stage of the scheduling process to: (a) check all the data related to the batches by using the EXPLORE option, and (b) revise and change the initial input data with the UTILITIES option. When changes are introduced through this last option, the scheduling process has to start again.

#### 10.3.3.2 - Creating the Drum

The next step in the constraint exploitation is to level the Ruins by taking into account the constraint capacity so that each resource unit only performs one order at a time. The Ruins metaphor is continued at this levelling step by imagining a bulldozer pushing the blocks backward to a level which equals the number of resource units available. In levelling the Ruins, the sequence of the batches is maintained so that a block whose end date appears after the end date of another block will maintain their relative positions. At this stage, no batch is made later so that although WIP can increase, every batch has got at least the whole shipping buffer left before the due date (see Figure 10.5).

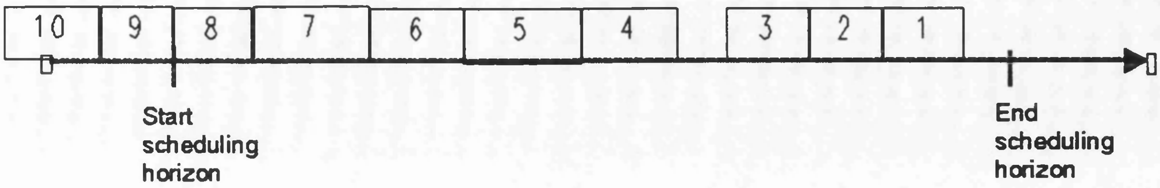



**Figure 10.5**: initial Drum

By pushing the blocks backwards along the time axis it can have resulted that some batches ended up requiring processing before the beginning of the scheduling horizon. This is not a feasible solution, therefore, the bulldozer must be used again to push the blocks forward so that the schedule starts from the present (the start date of the scheduling horizon). This process is done by the DRUM module and the schedule generated receives the same name (see Figure 10.6).

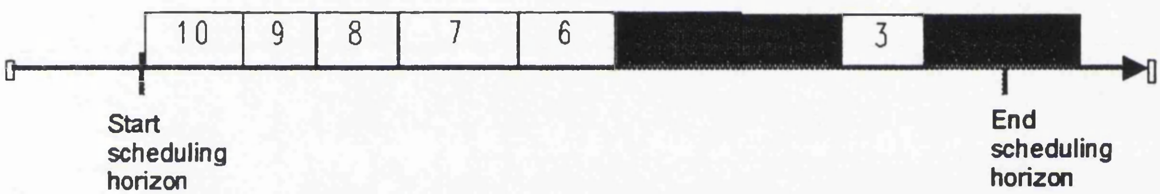



**Figure 10.6**: final Drum

In creating the Drum by pushing the blocks forward, three different circumstances can happen to the batches:

1- The batch will still be completed a whole shipping buffer before its due date.

2- The batch will be completed nearer to its due date but there will be at least half the shipping buffer left. In this case the buffer allocated to protect the system against production disturbances has been reduced. However, DISASTER maintains that there is still enough time to reach shipping without delay, and no further actions are suggested.

3- The batch will not be completed on the constraint until a time within half a shipping buffer of the due date or -even after it-. This represents a conflict in the Drum that must be resolved (DISASTER displays these blocks in red).

#### 10.3.3.3 - Removing the conflicts from the Drum

At this stage of the scheduling process the user faces the possibility of late batches. Is time for him/her to make some decisions as to how the impact of the delayed batches can be reduced.

DISASTER was designed on the assumption that no computer program would be able to replace intuition, knowledge and experience of the people involved in managing the resources. Therefore, the approach to this problem was to create a program that gives the user the possibility to assess the impact of the decisions taken by calculating and displaying the results. DISASTER provides the user with the EXPLORE option in which he/she can apply the following alternatives (ordered as it is suggested by DISASTER's vendors):

1- The first action to be taken is to check the data of the batches. Not only the data of the red blocks has to be revised, but also the data of the other batches because correcting some of them would imply that other more critical ones could be moved backwards and be performed earlier.

2- The second step is to check the material availability for the batches that are scheduled early in the Drum. If some material is missing, the batches should be manipulated accordingly (i.e. delaying their production or cancelling their order from the initial demands).

3- The third possibility is to try to reduce the time spent in set ups. In the initial calculation of the Drum, the set up time is included in the load of the batches. However, DISASTER assumes that whenever two batches process the same product, 'gluing' them together only a single set up would be required. This will make some batches be processed early and increase WIP, but with the price of increasing constraint available time, and thus, throughput.

The EXPLORE module provides two options for saving set up time:

3a) Automatic set up saving. It reorders the batches following these three rules: (I) searches from the earliest to the latest batches to find batches to move, (II) no batches will be made late or later, and (III) no batches will be moved if their movement will not help throughput.

3b) External definition of a set up ratio. This is the ratio between the time that is going to be saved and the time that the system is allowed to reach into the future. For example, a number 100 will be interpreted as requiring the system to look 100 hours into the future in order to save one hour of set up time. However, moving some works backward in time make other blocks be pushed forward and this may deteriorate the initial Drum (as opposite to the automatic rule). Therefore, the user must check the impact of different ratios before selecting the appropriate one.

4- When all the set up saving options have been exhausted, the next option the user can employ is overtime.

Initially, in the PARAMETERS module, the user has to define the amount of overtime allowed per day, per weekend, and per week. In this way people fatigue is taken into consideration.

Overtime will only be used for enhancing throughput; thus, the trigger to consider overtime are the red blocks. There are two types of overtime allocation: (a) automatic overtime (DISASTER automatically allocates time as close as possible to the first late block, and moving backward in time until: either the block is no longer red, or the start of the scheduling period is reached) and (b) manual overtime (performed by the user by defining the amount of overtime applied in a selected batch).

5- Another available option of the constraint exploitation stage is batch splitting. The split batch option will be useful whenever the batches are for different customer who have different due dates or part delivery is of benefit of the customer.

6- Ultimately, the only possible solution left is offloading some parts from the constraint to another resource, or otherwise, override the initial overtime limitations by having a much bigger period of overtime.

If all the opportunities for removing the late batches have been exhausted and there are still some blocks in red, the user has to accept that some orders will be late. DISASTER offers the option "Late Order list" that displays the late orders and the magnitude of the delay. At this point, the user can warn the customer about the expected late delivery.

### 10.3.4 - Subordination of the rest of the system to the Drum

When the options for increasing constraint available time are exhausted, the exploitation stage can be considered over and the Drum is then created. The next step is the subordination of the rest of the resources to the Drum, so that they support and protect the constraint schedule efficiently (i.e. without starving it from parts and employing the minimum inventory possible against production disturbances).

DISASTER assumes that subordinating the activities of the rest of the plant to the Drum can be achieved without the generation of individual schedules for each resource. As, by definition, non-CCRs contain excess capacity, all that is required at the subordination stage is: (a) release material to the shop floor at a rate determined by the Drum (otherwise, unnecessary inventory would be introduced to the system) and (b) instruct the workforce to work on the material as soon as it arrives.

The above methodology mirrors the Drum-Buffer-Rope scheduling method. In order to implement it in the subordination process, DISASTER first requires the definition in the PARAMETERS module of the (a) constraint buffer (the time required for the material released to the plant reach the constraint resource), and (b) assembly buffer (the time required for the material released to the plant reach the assembly point).

Once the buffers are defined, the Rope (material release schedule) can be calculated straightforwardly by simply subtracting the appropriate buffer from the Drum that has already been defined (for products that do not pass through the constraint on their route, the shipping buffer is subtracted from the order due dates to obtain the Rope).

DISASTER checks (a) the validity of the Rope and (b) possible conflicts between the Drum and the non-CCRs downstream the constraint by starting from the last day of the scheduling horizon and scheduling backwards one day at a time along the time axis. Finite resource capacity is taken into account to examine the existence of "non-instant availability" at the non-constraint resources. This concept refers to the fact that, although in overall non-constraint resources contain excess capacity, temporary loads (production peaks) may take place when several batches are scheduled for the same moment in the same resource. DISASTER tackles this problem by pushing the peaks into the past so that the daily loads are consistent with the available capacity.

Pushing the peaks into the past can originate conflicts with the already determined Drum and Rope. When this occur, DISASTER uses the mechanism called "Dynamic Buffering" to extend or cut the length of the buffers so that the conflicts caused by the temporary overloads are avoided.

At the end of the subordination process, the three cases explained in the following sections can take place.

#### 10.3.4.1 - No conflicts arise in the subordination process

When subordination is performed without originating any conflict between non-CCRs overloads and the Drum or the Rope, the output files described in section 10.2.2 are produced.

#### 10.3.4.2 - First Day Loads

When temporary overloads take place in the resources upstream the CCR and (a) the buffer cannot be cut (because this will delay the manufacture of a product and starve the CCR) or (b) extended (as it would mean starting further beyond the first day) DISASTER shows that there is not enough capacity to perform some operations and places those jobs at the beginning of the scheduling horizon. This is defined by DISASTER as a "First Day Load" conflict. Now the user has to solve it with the aid of the same DISASTER options available in the original constraint exploitation stage:

1- Data related to the orders that have caused the load is shown in the EXPLORE option, so that the user can check it and decide whether to modify it, off-load one operation to another resource, split the batch, or increase the amount of overtime available.

2- Another possibility is to ignore the problem because the user, through experience, may know that maybe the data is not representative of the true situation or that the conflict may be resolved very easily on the shop floor (e.g. temporal allocation of more staff).

3- The final alternative, is to declare the overloaded resource as the next constraint and create a second Drum. By this, the user is assuming that it is not enough to release the material to the plant according to the Rope, and that the new identified constraint capacity has to be increased by rescheduling its operations.

The process employed for dealing with the second constraint is identical to the one used for the first constraint, but with the additional complexity that both Drums cannot be in conflict with each other.

<u>+ Fixed drum violation case</u>

In the case of interactive constraints (i.e. one resource constraint feeding another one), DISASTER manipulates their loads by using the "Rod" concept. The Rod represents half of the constraint buffer and is placed between the interactive constraints to protect their outputs from production disturbances. The Rod is set half the constraint buffer as a balance between an excessive delay in shipping the order -if the whole constraint buffer is applied- and the possibility of "starving" the downstream CCR due to the action of production disturbances -if no buffer is employed-.

The Rods attempt to synchronize the activities of the second Drum with the activities of the previous Drum. However, if Rods for the second Drum cannot be located on the determined places (because they will cause a conflict with previous schedules), then a "Fixed Drum Violation" case arises (see Figure screen next page). The user has to solve this new conflict with the tools provided in the EXPLORE option.

#### 10.3.4.3 - Red Lane Peak

The final situation that can take place in the subordination process deals with the resources that are fed by the resource constraint. DISASTER, as in the above case, follows the backward finite scheduling procedure to check if the batches performed by the constraint can be shipped by their due date. During this process, some peaks of load may arise and if they cannot be moved backward because that would mean scheduling them before the constraint, then a new conflict is originated. This situation is given the name of "Red Lane Peak" (indicating that work that has passed through the constraint must be rushed out of the factory).

The user is offered the same variety of options to solve this conflict that those available for the "First Day Load" (i.e. overtime, offloading, changing due dates or ignoring the problem). Again, the option of defining a new constraint and create another Drum is also available.

### 10.3.5 - End of the subordination process

Once all the conflicts of the subordination process have been removed, DISASTER generates the output files that include details about the Drums and Ropes (among others). The whole iterative process of identification, exploitation and subordination has converged, and a final schedule has been created by the application of the DBR scheduling technique.


S C H E D U L E Version 1 Project: NET141
Schedule
Explore
Utilities
Help
Quit
Rod Display
Actual Units
Current
Dstnce Fwd = 0:00
Rod Length = 8:00
h Details
08/05/90 07:34
08/06/90 00:43
08/05/90 07:34
Rod Type Rod Length Batch Time Unit Drum
Hours of Load (0:46 per cell)
Display the rods for this batch
Drum
Thu Jun 09 09:20:07 1994

# 11 - EVALUATION OF DISASTER

## 11.1 - Introduction

This chapter evaluates the following DISASTER scheduling software features: firstly, the general definition and structure of the package is judged. Secondly, DISASTER's theoretical base is assessed according to the way it incorporates the TOC concepts and the general production scheduling principles. Thirdly, the software is compared with other scheduling approaches and with OPT. Fourthly, DISASTER's applicability is examined (a) modelling different production situations and investigating its operational features and the feasibility of the schedules with the aid of a simulation package, (b) visiting companies that are using the package, and (c) highlighting the more suitable production environments for its application. Finally, a short comment of DISASTER's latest developments and strengths is presented.

## 11.2 - DISASTER: Information System or Decision Support System?

Goldratt (1990b) understands an information system as the tool capable of providing the decision makers -managers- the required information so that they can answer precisely to the questions they encounter (see section 10.1.1). Moreover, the 5 focusing steps is the generic decision process that turns data into information. DISASTER, as being based on the 5 focusing steps, represents the computerized tool that would allow obtain the required information from the data bank.

Many other authors have extensively studied the information systems field. For example, Kroenke (1989) defines information as "the knowledge derived from data"; while data depict the recorded facts and figures. Gremillion and Pyburn (1988) understand data as "the symbolic representation of entities and events", information is "data that has been processed into a form useful for human decision making", and the act of transforming data into information is defined as *data processing*. According to these definitions, Goldratt's views correlate with other authors' points of view.

### 11.2.1 - Defining Information Systems and Decision Support systems

In general, information systems are thoroughly analyzed by authors like Gremillion and Pyburn (1988), Keen and Scott Morton (1978), Kroenke (1989), and Sprague and Watson (1989). Table 11.1 summarizes a classification of the information systems made by (Kroenke 1989).

| Type | Purpose | Characteristics |
|---|---|---|
| Transaction Processing Systems (TPS) | Support operations | » Operate on detailed record of the organization activities.<br>» The applications are standardized.<br>» Performance and reliability are critical (they must provide quick response and without failures).<br>» Is the oldest type of the information systems, and the underlying technology is relatively stable. |
| Management Information Systems (MIS) | Support management of operations | » They produce summarized, standard reports.<br>» The reports are regular and recurring.<br>» Since management relies on the output of the MIS, the reports must be timely and reliable.<br>» The reports contain simple models with static structure.<br>» The underlying technology is stable. |
| Decision Support Systems (DSS) | Support decision making | » They are better viewed as facilities having data and data manipulation tools than as standard systems.<br>» They are used to respond on an ad hoc basis to problems and opportunities as they develop.<br>» Flexibility and adaptability are critical.<br>» They often involve models of business activity and model building.<br>» Technology is evolving. |
| Office Automation Systems (OAS) | Support office communications | » They are multimedia (process data, text, graphics, illustrations, voice, etc..).<br>» Their structure is standardized, but particular applications may vary.<br>» Their primary goal is communication, and hence, interconnectedness and reliability are critical.<br>» The technology that supports OAS is exploding. |
| Executive Support Systems (ESS) | Support senior executive information needs | » They are the newest information system type.<br>» They provide highly aggregated information in frequently standardized formats.<br>» Integrate many sources of data.<br>» Timeliness and accuracy are vital.<br>» The initial executive reluctancy towards the information systems is slowly changing.<br>» Technology is gradually evolving. |

**Table** 11.1: types of information systems (source: Kroenke -1989-)

Keen and Scott Morton (1978), and Sprague and Watson (1989) understand information systems (commonly called *Management Information Systems -MIS-*) as:

» Focused on structured information tasks where standard operating procedures, decision rules, and information flows can be reliably predefined.

» A system that integrates the data from the business functions (e.g. production, marketing, personnel, etc..).

» The relevance for managers' decision making has mainly been indirect, for example, in the inquiry and report generation from a database.

Similarly, Decision Support Systems (DSS) are interpreted as (Keen and Scott Morton -1978-; Sprague and Watson -1989-; Gremillion and Pyburn -1988-):

» Designed to help in making decisions in problem areas in which there is sufficient structure for computer and analytic aids to be of value but where managers' judgment is essential in making the final choice.

» DSS extend the range and capability of managers' decision process to help them improve effectiveness by providing a variety of flexible and quick analytical tools and data.

» They are an interactive supportive tool for managers, which does not attempt to automate the decision process, predefine objectives, or impose solutions; only help the manager explore aspects of the problem.

### 11.2.2 - DISASTER as a Decision Support System

From the above definitions DISASTER should no longer be considered as an information system, but rather it should be interpreted as a Decision Support System. The aspects that make DISASTER a Decision Support System are:

▸ According to DISASTER's vendors, the goal of the package (when the three phases are operational) will be "to answer any business question that any manager in the 'Throughput World' might pose to it" (AGI DISASTER manual 1990). This goal coincide with other authors understanding of a DSS (e.g. Kroenke -1989-: DSS are used to respond at problems as they develop).

▸ The architecture of an information system defined by Goldratt (1990b) (see section 10.1) resembles more the structure of a DSS than the one of a MIS. For example, extracted from the previous section, DSS-s are normally based on computer or analytic aids employed to treat the data available in order to help the managers make decisions. Similarly, Kroenke (1989) views DSS as facilities that have data and data manipulation tools.

▸ DISASTER's options represent the analytical aids that permit the assessment of different alternatives.

▸ Finally, one of the basic fundamentals of DISASTER is the user interface capability. This possibility enables the user take active part in the decision process by commanding the decision course (corresponding with the capabilities attributed to a DSS).

### 11.3 - Assessing DISASTER's theoretical basis

The assessment of DISASTER's underlying philosophy will be centred firstly in the analyis of the way the TOC concepts are contemplated by the software. Then its location in the production management philosophies will be pointed out. Finally, DISASTER's relation with the general production management principles will be reviewed.

#### 11.3.1 - DISASTER and the TOC concepts

The way DISASTER embraces the TOC's concepts, assumptions and techniques pointed out in chapter 6 are reviewed in this section.

+ <u>TOC's production management concepts</u>

» *<u>The Goal</u>*. The way DISASTER seeks to achieve the Goal of maximizing throughput while simultaneously minimizing inventory and operating expenses is:

(a) DISASTER's vendors maintain that if maximum throughput is not achieved by applying the schedules produced by the software, a policy constraint must exist on the shop floor.

(b) It keeps inventory to a minimum by releasing material to the plant at the rate dictated by the Drum (Rope).

(c) It limits operating expenses by defining the maximum overtime allowed to be allocated.

However, there are two aspects related to DISASTER's fundamentals that influence the achievement of the Goal:

1- The active role the user plays in DISASTER makes it a tool subject to human errors. The user can always make the wrong decision (e.g. choosing a constraint, assigning overtime, offloading, selecting the buffers length, or even introducing the initial data) that would lead to a schedule far from being the optimal one (optimal in the sense of achieving the Goal).

2- Even if the user is able to make the best possible choices, DISASTER is based on heuristic rules, and thus, its schedules cannot be considered optimal (only satisfactiry solutions can be achieved applying heuristic approaches).

» *The POOGI*. the final TOC objective is to establish a Process of on Going Improvement so that the system will continually move towards the Goal by focusing on the efficient exploitation of the constraints. The indispensable involvement of the user in DISASTER's scheduling process make him/her to become aware of the problems that need to be solved and facilitate the application of the improvement efforts in the adequate places.

» *Operational measures*. DISASTER's input files do not include any data related to final product prices or production costs (i.e. operation costs, scrap, inventory costs, overtime, workforce cost, etc..). Consequently, the operational measures analysis is a task that cannot be carried out by DISASTER.

» *Bottlenecks vs non-bottlenecks*. DISASTER does not make any difference between a bottleneck and a non-bottleneck resource in the load/capacity list displayed in the Identification option. It leaves the user the option to choose any of the resources as the CCR and applies the same scheduling procedure for a bottleneck and for a non-bottleneck.

» *The 5 focusing steps decision process*. the 5 focusing steps generic problem solving approach is the essence of DISASTER decision support system. The first three of the 5 focusing steps (as being included in the Drum-Buffer-Rope scheduling technique), are implemented in DISASTER phase 1: scheduling.

The next step (i.e. elevate the constraint), can also be considered contemplated in DISASTER's simulation -What if- capabilities. The impact of proposed solutions and new investments (e.g. inversion in new equipment, process time reductions, workforce -capacity- increase, etc..) can be assessed before they are accomplished in the shop floor.

Finally, the last step (i.e. start again with the process if the constraint is broken, and do not let inertia be the constraint), is something related to the human nature (inertia). However, the simple way in which the user can apply DISASTER's operational functions and command the scheduling process may encourage his/her interest in scheduling and break inertia as the 5 focusing steps constraining aspect..

» *Production phenomena*. production disturbances can either be handled by the non-bottleneck inherent excess capacity -protective capacity- ('catch up' possibility), or by the utilization of inventory buffers -protective inventory- (decoupling operation dependency) in front of the critical parts of the system. DISASTER incorporates these two measures in the following way:

1- Protective capacity: by definition, non-bottlenecks are the only resources that contain excess capacity. However, temporary peak loads can absorb the available excess capacity ("non-instant availability" concept) and leave disturbances spread along the system. To avoid this undesirable situation, DISASTER permits the user introduce in the parameters option the level of protective capacity non-CCRs should contain to absorb the spread of disruptions. This protective capacity is taken into account during the subordination process by leaving unscheduled the percentage of non-CCR capacity defined in the parameter.

2- Protective inventory: DISASTER incorporates this concept in the following two ways: (a) at the initial definition of shipping, constraint and assembly time buffers in the parameters option, and (b) at the "arrow" input file, where there is the option of defining inventory buffers for particular operations.

Moreover, DISASTER colours in red the batches that are scheduled with less than half of the buffer left to highlight that production disturbances are more likely to affect their completion.

+ TOC's scheduling concepts and techniques

» *Drum-Buffer-Rope scheduling technique*. DISASTER must be considered a clear computerized application of the DBR scheduling technique. It accommodates the whole DBR concept:

(1) Identify the constraint and exploit it to its fullest (Drum).

(2) Protect the Drum (the "heartbeat" of the system) from production disturbances by placing Time Buffers in front of the critical parts of the system (i.e. constraint, assembly and shipping).

(3) Subordinate the rest of the system to the constraint pace by timing the release of material to the DRUM (ROPE), and then making the resources work in the parts as soon as they arrive.

» _9 scheduling rules_. The particular interpretation DISASTER makes of the rules is:

- Rule 1> Balance flow not capacity. DISASTER accomplishes this rule by creating a schedule that matches constraint output with demand. Then, tries to synchronize flow by subordinating the rest of the system to the constraint Drums.

- Rule 2> Constraints determine non-constraints utilization. Non-constraint resources will only process parts at the rate determined by the constraint pace. Material is released to the plant according to the Rope (that is based on the constraint schedule - Drum-).

- Rule 3> Utilisation and activation of a resource are not synonymous. DISASTER guarantees that resources are utilised -and not activated- by the timed release of material to the shop floor (Rope) that assures throughput by maintaining inventory to a minimum.

- Rule 4> An hour lost at the bottleneck is an hour lost for the entire system. This rule is in consonance with DISASTER's way of working in those cases where the constraining resource is a bottleneck (DISASTER fully loads the bottleneck). However, if the CCR is a non-bottleneck, DISASTER schedules it so that due dates are met but keeping it idle when its production would only lead to increase inventory.

- Rule 5> An hour saved at a non-bottleneck is just a mirage. Similar to rule 3, DISASTER follows rule 5 by activating the non-constraint resources only when their output contributes to accomplish the Drum (Rope).

- Rule 6> Bottlenecks govern both throughput and inventory. This rule is a consequence of the DBR scheduling technique application (i.e. the Drum determines the throughput and the Rope the inventory).

- Rules 7 and 8> Transfer batch should not always equal a process batch and process batches should be variable not fixed. DISASTER creates the Drum defining the proces batches the same size as the customer orders and does not specify any transfer batches size. Similarly, in the subordination process the size of the releasing product batches (Rope) equals the final order size and also the definition of the size of the transfer batches is left in shop floor personnel hands (DISASTER assumes that batch overlapping can be performed but does not determine the appropriate process and transfer batch sizes).

- Rule 9 > Set the schedule by examining all the constraints simultaneously. This rule refers to the simultaneous consideration of finite capacity and priority while creating the schedule. DISASTER, even if it does not consider these two concepts simultaneously, avoids suboptimization by sequentially exploiting the identified constraints (taking into account their finite capacity) and assigning priorities that are not in conflict with previous constraint schedules.

### 11.3.2 - DISASTER and the production management philosophies

Chapter 3 described the way the three most important production philosophies managed production scheduling: (1) MRP/MRP-II's "top down" approach, (2) JIT's holistic approach, and (3) TOC's efficient management of the shop floor operations ("bottom up" approach).

DISASTER and OPT scheduling softwares, being DBR-based computerized systems, should be considered "bottom up" approaches that take into account resource finite capacity to realistically represent the limitations of the shop floor. However, DISASTER -like OPT- has a holistic vision of the system (JIT approach) by focusing on the constraints and subordinating the rest of the resources to their optimum schedules. In this way, local optimums equal global optimums and suboptimization is avoided.

### 11.3.3 - DISASTER and the general production scheduling principles

DISASTER comprises the general production scheduling principles in the following way:

» <u>Principle 1: there is no universal scheduling solution</u>.

DISASTER's originators claim that the software -once it is completed- will be able to answer any question managers may pose to it. They further restrict this statement by declaring that DISASTER would be the appropriate information system -DSS- for the managers immersed in the "Throughput World" due to its foundation on the 5 focusing steps.

According to this, the package should not be judged until the three phases are operational (i.e. scheduling, control and What if). However, from what has been accomplished so far (the scheduling phase), DISASTER should be considered a proprietary solution that applies a simple heuristic algorithm to give specific solutions to shop floor management problems. Moreover, the more suitable production environments for DISASTER implementation will be reviewed in section 11.6.3.

On the other hand, the user involvement in the scheduling process is a step forward in the POOGI achievement.

» Principle 2: a feasible schedule cannot contain any conflict between the constraints of the system.

DISASTER follows this principle by sequentially identifying the constraints and creating their particular Drums, but warning the user when conflicts with previous Drums take place ("Fixed Drum Violation"). At the end, when the user has been able to solve all the conflicts, realistic schedules are produced in which all the constraints are equally treated and none of them is suboptimized.

» Principle 3: production disturbances should be taken into account while developing the schedule.

DISASTER handles production disturbances by locating time buffers in front of the critical parts of the system (protective inventory), and maintaining unscheduled a percentage on the non-CCR capacity (protective capacity).

» Principle 4: schedules must be evaluated according to the achievement of certain objective/goal.

In all DBR-based approaches, throughput is ensured by making the best use of the constraint resources (optimum schedules) and maintaining inventory to a minimum applying the Rope concept.

» Principle 5: there must be a match between the scheduling technique and the production environment.

DISASTER, as it is extensively analyzed in Appendix D -and mentioned later in section 11.6.2-, lacks certain modelling capabilities that would permit represent all the production situations. Additionally, it assumes that the company in which is installed does not contain any policy constraint (they are all broken). Furthermore, with the purchase of the software, the company is bound to attend a training program on the TOC concepts (the company accommodates to the underlying philosophy of the package, and not vice versa).

» Principle 6: heuristic approaches will be utilized to solve most of the scheduling problems.

DISASTER applies a simple heuristic procedure explained in the following section.

» Principle 7: optimising isolated parts of the system does not necessarily produce optimum solutions for the whole system.

DISASTER, as being based on the DBR technique, achieves global optimum solutions by producing "near" optimum schedules for the constraints (avoiding any conflicts between them) and subordinating the rest of the system to them.

### 11.4 - DISASTER and the production scheduling approaches

DISASTER performs the schedules for the constraints (Drum) based on a very simple heuristic rule:

1- Sequence the batches by subtracting the shipping buffer from the customer due dates and assuming constraint infinite capacity (ideal schedule -'Ruins'-).

2- Place the batches in the initial order taking into account the number of available constraint resources (finite capacity). At this stage, the scheduling horizon -time- is still assumed unlimited.

3- Take into account time, and locate the batches in the determined scheduling horizon (pushing forward the batches located in the past -Drum-).

If conflicts arise in the Drum or in the subordination stage, the user is responsible for solving them by using the options provided by DISASTER (allocating overtime, offloading, saving setup, deleting some orders, reallocating the batches, etc..).

The optimality of the schedules produced can be highly questioned due to: (a) the utilization of the explained *heuristic rule*, and (b) the rely on human expertise to solve the production conflicts (DISASTER is subject to human errors -wrong decisions-).

#### 11.4.1 - Bottleneck approaches

Bottleneck approaches were divided in section 4.3 into (Morton and Pentico 1993): myopic dispatch approach, shifting bottleneck algorithm, bottleneck dynamics, and OPT's scheduling approach.

DISASTER -like OPT- creates an optimum schedule for the CCR and subordinates the rest of the system to it. However, it *iteratively builds a schedule for one constraint at a time* based on the just explained simple heuristic rule, and treats the results of previously scheduled resources as constraints for subsequent schedules. In a sense, this type of approach can be described as "myopic", since the downstream consequences of the decisions taken at each iteration cannot necessarily be recognized in advance. For example, non-optimal decisions taken in one stage may be further deteriorated in subsequent stages, and lead to a far from optimal final scheduling solution.

### 11.4.2 - Finite vs infinite capacity scheduling approaches

The assumption of infinite resource capacity generates unrealistic schedules and locates the responsibility of following the schedules and solving the problems onto the shop floor personnel. However, this can bring the benefit of making full use of personnel experience and involvement in the scheduling problem solving task (see section 3.1).

On the other hand, finite capacity scheduling approaches create schedules that realistically represent the limitations of the plant, but removes the responsibility of shop floor personnel on making scheduling decisions based on their experience.

DISASTER is a finite capacity scheduling software because it first creates the schedule for the identified resource constraint by taking into account its finite capacity, and then subordinates the rest of the plant to the constraint schedule, highlighting any capacity conflicts that take place (i.e. "First Day Loads" and "Red Lane Peaks"). However, DISASTER requires user's involvement and knowledge in solving the problems appeared in the scheduling process. The user commands the scheduling process and decides which actions to take when conflicts arise. In this sense, DISASTER has attempted to embrace the best of finite and infinite capacity scheduling approaches.

## 11.5 - DISASTER and the scheduling softwares

### 11.5.1 - DISASTER's location in a general framework of scheduling softwares

According to the classification of scheduling softwares made by Harrison (1993b) and exposed in section 9.4.1, most of the scheduling softwares fall into one the following categories: post MRP computerized planning boards, post MRP optimizing works order schedulers, 'rate of use' schedulers, and structured schedulers.

DISASTER -like OPT- would be included in this last group of softwares that optimize the sequence of jobs at the CCR and then try to synchronize the rest of the activities by matching non-CCR operations with CCR schedules.

### 11.5.2 - DISASTER vs OPT

DISASTER's similarities and differences with OPT are exposed in the following sections.

+ Principal similarities

Both OPT and DISASTER contain the following main features in common: DBR-based softwares, finite capacity systems, 'bottom up' approaches that require strict adherence to the schedules produced, both contain simulation capabilities, they are proprietary solutions based on heuristic rules, both seek the same Goal, and, finally, both recognize the existence of production disturbances in the system and try to tackle them.

+ Principal differences

The major differences are:

» Scheduling process divergences (scheduling driving force): in OPT, time represents the driving force of the schedule (CCRs are scheduled forward in time to their fullest from the beginning of the scheduling horizon) (Goldratt 1988). On the contrary, DISASTER uses the exploitation of the constraint as the schedule driving force (it does not schedule the CCR according to its available capacity, but according to the customer due dates). The consequences of this important difference are:

- DISASTER only fully loads the CCRs when they are bottlenecks; otherwise they contain idle periods between the scheduled batches. OPT, scheduling a non-bottleneck forward in time to its fullest, creates excess inventory (however, this is not totally true because OPT contains a mechanism to prevent excess build ahead -order permission-).

- OPT identifies and exploits all the CCRs at the same time. DISASTER leaves the user the possibility of selecting the CCRs and iteratively creates their schedules.

- OPT takes simultaneously into account resource capacity and priority while creating the schedules. DISASTER creates the optimum schedules for the CCRs sequentially (but avoiding any conflict between them).

- In OPT, once the optimum schedules for the CCRs have been created, the rest of the system is subordinated applying infinite capacity forward scheduling -for the critical part- and infinite capacity backward scheduling -for the non-critical part-.

DISASTER utilizes a radically different subordination procedure based on capacity planning (backward finite scheduling) and does not create detailed schedules for non-CCR resources.

» Incorporation of the realities of the system: OPT captures the product and process structures based on detailed and complex modelling capabilities (for example it can model -in contrast to DISASTER- different operation set up times and alternative resources at different production rates). In addition, the management policies are comprised in the management parameters (that have to be properly fine tuned to create realistic schedules).

DISASTER lacks some of the modelling capabilities of OPT, and it does not include management parameters to represent the production policies. However, it provides high interaction capabilities, powerful operational functions, and regards on the user's expertise to illustrate the particular shop floor practices. Moreover, it assumes that the policies are broken before the software is implemented.

Related to this, DISASTER's vendors claim that although there may be some characteristics of the environment that cannot be captured in the input files (e.g. dependent setups or alternative routings), the software also assumes that the data is subject to many errors and that the system is subject to statistical fluctuations, and addresses all these problems placing time buffers in specific parts of the plant.

» 'White box' vs 'black box': OPT is considered a 'black box' since it provides an output from the introduced input information utilizing an unknown algorithm. DISASTER on the contrary, is understood as a 'white box' since nothing is hidden from the user, and he/she can command the scheduling process. The user interface is organized around a series of menus which guide the user through options at each stage of the program. The user selects the actions that he/she wants the program to take and whether move down to a greater detailed information or carry on with the scheduling process. According to DISASTER's vendors, organizing the information in a hierarchy basis the two 'white box' principles are achieved: freedom and focus (AGI DISASTER manual 1990).

Furthermore, DISASTER's schedules, as being created by the user, can be considered intuitive (in contrast to the counter-intuitive OPT schedules).

» POOGI consideration: as a result of the above characteristic, DISASTER may increase the interest in scheduling and encourage the user in solving the scheduling problems (POOGI). OPT may reduce the interest in scheduling as it will always provide a 'near' optimum solution and does not encourage user's involvement and participation in the scheduling process.

» Simulation tool: both softwares can be used as production simulation systems. However, DISASTER -in contrast to OPT-, due to its interactive capabilities, permits reactive corrections without having to run the whole model again. Moreover, the computing time required to create solutions is smaller in DISASTER than in OPT (although both contain the files in on-line memory).

- Handling production disturbances: DISASTER utilizes protective capacity and protective inventory to tackle production disturbances. OPT, apart from locating time buffers in front of the critical parts of the system (protective inventory), spaces the jobs to create safety times between the operations and avoids scheduling parts immediately after their schedule completion in the previous operation (Goldratt 1980).

- Implementation time: the time required to implement the software should be considered higher for OPT than for DISASTER due to (a) its extensive and complex modelling capabilities and (b) the necessity to fine tune the management parameters to realistically represent the production behaviour.

- Required data: as a consequence of OPT modelling requirements, the data it requires is higher than the one needed in DISASTER.

- Applicability: OPT will be more capable of representing the realities of the manufacturing systems. DISASTER, although it cannot compete with OPT in this area, it may produce as valid schedules as OPT by using the scheduler's knowledge to implement the options that OPT does automatically.

- User friendly: DISASTER is without any doubt more user friendly than OPT.

- Easy to learn: again, DISASTER is easier to learn than OPT.

- Price: DISASTER is much cheaper than OPT (around £2000 in contrast to OPT's £100000-£200000).

- Lack of reported cases: there are many published papers reporting -most of the time- successful OPT implementations. On the other hand, there is not a single reported DISASTER installation (the reason may be the relatively recent release of DISASTER to the market -around 1989-).

+ Which package is better?

None of the packages can be considered better than the other. OPT has brought astonishing benefits for most of the companies that have implemented it. However, its high cost, 'black box' solution characteristic, modelling and continual data maintenance requirements, and accurate management parameters set are drawbacks to take into account while deciding its purchase.

DISASTER is a much cheaper software that cannot compete with OPT's modelling capabilities but that compensates this weakness with high interaction options, powerful operational functions, and easy to learn and use features. Its possibilities are unproven yet, but cases of successful DISASTER implementations can already be found (they will be examined in section 11.6.4).

## 11.6 - Applicability of DISASTER

### 11.6.1 - Use of DISASTER in the organization

DISASTER can be a helpful tool for the following company functions:

» Detailed shop floor scheduling: definitively, DISASTER is a scheduling software that coordinates the shop floor activities and ensures that customer due dates are met. It tries to produce the maximum throughput by maintaining inventory and operating expenses to a minimum.

» Management of production: DISASTER can also be of assistance in the management of production by, for example, displaying (a) the resources upon which overtime will be required in the future in order to maximize throughput (warning of overtime requirements in advance will help improve employee relations), (b) temporary resource overloads (so that work can be offloaded or subcontracted ahead on time), (c) critical resources to be protected from production disturbances, (d) early material release to the shop floor to fully exploit the key resources, etc..

» DSS for sales decision making: information about whether a product uses under-utilized (non-CCR) resources, or, on the other hand, requires overtime or passes through a CCR on its route, would affect the final cost of the product. This information, added to an accurate determination of the shipping date will be of major benefit for the sales department. More accurate product pricing and realistic assessments of the capabilities of the plant will make the company fulfil its promises and achieve a greater customer service and satisfaction.

» DSS for strategic planning decisions: the 'What if' capabilities of DISASTER will serve to realistically check the impact proposed actions would have in the system (e.g. investment in new equipment, introduction of another shift in a particular department or resource, reduction of the scheduling horizon, inclusion of urgent orders, impact of setup time reductions in specific machines, etc..). The 'What if' capabilities will help the company make decisions related to (a) the opportunity to enter a new segment of the market with a new product, (b) the possibility to realistically determine how much the company has to invest to satisfy certain product demands, or (c) the number of operators that need to be hired for a determined period in order to answer demand.

### 11.6.2 - Assessing DISASTER under different production situations

DISASTER's schedules, modelling capabilities and operational features are thoroughly examined in different production environments in Appendix D. Extracted from that study, the following weak points of DISASTER can be summarized:

» Modelling capabilities: the common shop floor practices (policies) that cannot be accomplished in DISASTER are:

a) Batch overlapping: DISASTER does not contemplate different process and transfer batches, and leaves the responsibility of defining them to the shop floor personnel.

b) Minimum or maximum batch sizes normally utilized in certain situations to optimize particular resources (e.g. painting stations or furnaces) cannot be defined in DISASTER.

c) Production offloading, setup time savings and batch splitting can only be performed for the resources defined as constraints (while in reality, these are common practices for all the resources of the plant indistinctly).

d) Same purchased material with different delivery times: sometimes there is more than one vendor for the same part and is highly improbable that they all have the same delivery time. This circumstance cannot be contemplated in DISASTER.

e) Dependent setup and alternate routes: both practices are not included in the software (however, both of them will be included in the latest versions).

f) Different parts with the same setup procedure (Patterson 1993). This situation occurs in some environments, but DISASTER only allows to save setup time by 'gluing' the batches that process the same part.

Similarly, the following special production cases will hardly be adequately represented in DISASTER:

a) Limited inventory space: DISASTER assumes unlimited inventory space (the user has to take this fact into account while defining the constraint, assembly and shipping buffers).

b) Different lead times from the constraints to shipping: this particular situation is not properly addressed by the software due to the definition of the same buffer size for all the constraints.

c) A constraint processing more than one part for the same product: as both constraints have the same due date, DISASTER will independently sequence their operations. However, their correct sequencing will have important effects in the achievement of a good due date performance (see Case 1 in Appendix D).

d) A close to balance system (interactive constraints): DISASTER's iterative procedure involves identifying all the constraints of the system one after the other and solving all the conflicts that arise between them (First Day Loads, Red Lane Peaks and Fixed Drum Violations). This problem solving task will be hard and time consuming in complex manufacturing systems. Plenert (1993) maintains that Linear Programming will avoid this extensive iterative process and will immediately provide the optimal solution.

Moreover, it has to be noticed that the defined buffer sizes are indiscriminately applied to all the identified constraints (even if they are initially defined for the first constraint).

e) Long setup times: as set up times are not included in the identification option this can mislead users appreciation of the available capacity. Then in the Drum the conflicts caused by the long setups will have to be solved.

» Operational features: the weaknesses that can be found in DISASTER's operational features are:

a) Overtime allocation: the overtime allocation option of the First Day Load and Red Lane Peak cases overlooks the limitations defined by the user in the initial parameters, and sometimes may not be in consonance with the real overtime required (sometimes with less overtime the Drum can be properly protected)(see Cases 3 and 4 in Appendix D).

b) Set up ratio option: this option may cause more problems than the ones it is supposed to solve (see Case 2 in Appendix D).

c) Data modifications: whenever a single data is modified, the scheduling process has to start again from the beginning.

d) Manual reschedule: this option applied in close to balance situations has to be carefully utilized or may cause more problems than benefits (see Case 2 in Appendix D).

e) Final output files: the final outputs are presented in a text format and have to be processed by an external software to be able to be interpreted.

» Schedule evaluation: some of the weaknesses encountered in the schedule aspects assessed are:

- Feasibility: in isolated cases there was a lack of coherence between the Drum and the Ropes that produced unrealistic schedules (Case 1, Appendix D).

- Objectives achievement: in some cases, throughput would have been increased if a different schedules were applied (Case 1, Appendix D). Inventory, on the other hand, is highly dependent of the appropriate definition of the buffer sizes; while, operating expenses could be reduced with more sensible allocation of overtime in the First Day Load and Red Lane Peak cases.

- Immunization against production disturbances: the adequate protection of the system depends on the realistic definition of the time buffers and protective capacities of non-CCRs (they have to be in consonance with the inherent behaviour of the system: resources inherent fluctuations, predictability of the process times, resources unreliability, etc..).

### 11.6.3 - DISASTER and the manufacturing systems

As it was pointed out in OPT's applicability analysis (see section 9.4.2.3), the appropriateness of a scheduling software for certain manufacturing systems will depend on how well (a) it models the static and dynamic parts of the system and (b) it incorporates the management policies. DISASTER's modelling limitations have already been remarked in previous sections. However, its robust interaction capabilities that utilizes users' expertise may permit create valid schedules that surpass the modelling limitations.

As a result, complex batch production situations may be -according to the individual environment characteristics- adequately scheduled and controlled by

DISASTER. However, the more suitable manufacturing systems for DISASTER implementation would be: fairly simple environments (simple batch manufacturing situations), with stable demand (repetitive production lines), predictable process times (to avoid continual rescheduling), and limited number of constraints (to reduce the possibility of conflicts between them).

On the contrary, manufacturing systems with large number of process plans - alternate routes- (job shops), and poorly defined production routes (project) would require too much structure for DISASTER to create their models. Finally, close to balance systems (certain repetitive production lines and continuous processes) would find greater benefits in more simple scheduling techniques than the ones contained in DISASTER.

### 11.6.4 - DISASTER implementation case studies

The following case studies obtained from personal contact exhibit some successful and unsuccessful DISASTER implementations.

+ <u>CASE-1: PERKSON Limited</u>

- <u>Company background</u>: Perkson Limited is a medium/small size company -130 employees- located in Stourbridge (West Midland). It is a traditional batch manufacturer with a high variety of final products (up 1000 different ones) that range from all shape and size of forging items, security and conveyor products, and commercial vehicle components. Perkson designs and produces the saleable items normally in an individual basis to answer specific customer requirements; although they also have some standard products made-to-stock and then sent to distributers and a last group of few products that are stocked for important customers.

The manufacturing system contains 70 general purpose machines (hammers, drillers, cold pressers, lathes, saws, milling machines, etc..) located in a functional basis and is characterized for a very complex and chaotic production flow (most of the products pass through all the work centers). All the processing operations are performed in site, unlike painting and heat treatments that are subcontracted. Due to the small batches, make-to-order fabrication style (a) resource productivities are low (up to two changes of dies in the hammers per day), and (b) production scheduling and control result a difficult task.

- Problems in the past: in 1989, after reading Goldratt's book "The Goal", Perkson decided to apply the TOC principles to solve their production scheduling and control problems. The two company Directors attended a course of the TOC concepts, and installed a manual Drum-Buffer-Rope system. WIP dropped close to zero, and due to (a) the complexity of the manufacturing process, (b) lack of personnel education in the TOC principles, and (c) several production control mistakes that led to severe material stockouts (material 'stealing' was out of control) made the company lose many orders and be close to bankruptcy.

- New system implementation: in 1991, Perkson decided to buy a computerized shop floor scheduling system that would help them solve the problems encountered in the past. They searched for the TOC-based scheduling softwares available in the market (they also examined OPT) and decided to purchase DISASTER. The scheduler of the company attended in the USA the course given with the purchase of the software and DISASTER's implementation process began.

After 6 months gathering data from their own bespoke computer system, the first time they created a schedule in DISASTER took them 12 hours to solve all the conflicts caused by the more than 25 constraints they identified (even the standard DISASTER package could not cope with so many CCRs and had to be modified to accommodate to Perkson's particular situation). They also realized at that time that a thorough personnel education was required in order to follow DISASTER's schedules in the shop floor.

- Actual situation: Perkson is still using DISASTER to schedule and control the manufacturing operations. The software has been successfully integrated in their 'home made' system (employed to manage the manufacturing operations, control inventory and purchase, and deal with sales and marketing matters).

They are currently carrying out another education process on the TOC concepts to solve some shop floor schedule adherence problems (still now bottleneck resources stay idle at certain periods). However, the company Directors feel that the operators do not understand the principles (according to them because it is an imposed idea).

- DISASTER: DISASTER is currently used once a week to (a) produce detailed shop floor schedules (every Friday the scheduler generates the schedules for the next week) and (b) strategic planning decisions (calculate capacity requirements 6 months ahead to determine product quantities for the purchase of the products with long delivery times and estimate a production due date to communicate to the customer).

The minimum possible production capacity is employed to answer demand (capacity costs money) and this generates a system close to balance in which multiple interactive constraints take place (are common 5-6 major constraints and about 10 temporary ones). However, unlike in the past, due to the experience acquired using DISASTER, all the conflicts are easily solved and the schedules are created in 2-3 hours. Sometimes, after one hour of solving the conflicts with the Drums, they had to start the scheduling process again because they realized that the input data was incorrect or that they required more capacity in a specific resource.

Every week a different production mix is loaded to the software and the scheduling situation radically changes (the principal and secondary constraints are not always the same ones). They use all the options available in DISASTER to solve the interactive constraints problem (overtime, production offset, batch splitting, manual rescheduling); but never the setup savings options because of the high product diversity they have.

In manufacturing situations characterized by lack of overall capacity, production disturbances spread along the system and negatively affect throughput and inventory. Perkson handles production disturbances by following DISASTER's material release schedules (Rope) that accumulate inventory in front of the critical parts of the system (protective inventory) and by defining less resource capacity than the one really available (protective capacity). Furthermore, whenever production disturbances affect the schedules, they do not reschedule the whole plant (that would radically change the production situation), but rather, they rely on the inherent excess capacity to 'catch up' production.

Further particular DISASTER applications are:

a) Auxiliary reports containing non-CCR schedules are created and given to the foremen to warn them of the jobs that will arrive to their departments in the near future.

b) The die fabrication is included in DISASTER as another operation and is thus scheduled with the rest of the process stages.

c) They have created a special option that (a) determines the purchasing requirements and dates and (b) estimates the production dates, by linking DISASTER's process and set up times, with suppliers delivery times and die fabrication times contained in their own computer system.

d) Very small time buffers are defined in DISASTER's parameters and dynamic buffering is used to sequence the operations.

Finally, from Perkson's scheduler point of view, WIP records have to be accurately defined in order to obtain reliable schedules.

- Benefits obtained: DISASTER effectively controls and manages Perkson's complex production system. As a result, WIP has been dramatically reduced (increasing ROI, cash flow and reducing production lead times) and due date performance has increased from 65% to 90% (improving customer service). Moreover, the "end of the month" syndrome suffered in the past has disappeared.

Perkson's Directors maintain that without DISASTER they would not have survived last year recession, and now, with 70% more orders than in those critical times, DISASTER is still able to successfully coordinate the shop floor.

- Last comments: the key to DISASTER's success is based on two factors: (1) top managers involvement and commitment and (2) DISASTER's integration with their own computer system. However, the education process should be successfully carried out to obtain maximum benefits from DISASTER's use.

Finally, related to TOC, Perkson's Directors declare that the production philosophy lacks practicality and contains some confusing and erroneous concepts (e.g. the Thinking Process is found difficult to apply, multiple resource constraints do exist more often than TOC believes, and some TOC concepts are difficult to be taught to the shop floor personnel). Their next strategic concern is examine the market in more detail and try to exploit it to its fullest.

+ CASE-2: CARNAUDMETALBOX

- Company background: CarnaudMetalbox is a medium size company -430 employees- located in Poole (Dorset). It manufactures metal closures for the food industry (in 1993 they exported 40% of their production to Europe).

They have a quite simple manufacturing system formed of different product families manufactured in different production lines, and a final common operation in which the metal closure is performed (all the products contain this operation in its route).

- Problems in the past: in 1990, the company suffered from long lead times, poor average product quality and poor delivery reliability. They found that the main cause of these problems was the traditional style in which production operations were managed (e.g. large batch sizes -long run mentality-, reliance on stocks, and focus on production line efficiencies -local optima-).

- Management style changes: TOC was found as the adequate production philosophy that would help them solve the above problems and assure on time deliveries. The TOC concepts that were implemented since 1990 are (in the order they were installed): throughput time measure, gating control (manual DBR application), Buffer Management, batch sizes reduction, suppliers involvement, operators education process, DISASTER implementation, POOGI, Thinking Process.

- DISASTER: the software was first installed in August 1990. It took CarnaudMetalbox 4 months to gather and "clean" the production data extracted from their own production management system ("Material Management System").

Currently, DISASTER is used to perform capacity planning analysis and create the schedules in all the production lines once a week. The setup saving option and the multiple resource function (included in the latest DISASTER versions) are used to solve the scheduling conflicts. As a result, valid schedules are generated and high shop floor adherence achieved.

- Benefits obtained: with the application of the TOC concepts, throughput times have been significantly reduced, and delivery reliability has improved (customer service).

+ CASE-3: FAVAHE

- Company background: Favahe is formed of three different companies: Acesa, Palmera, and Irimo that are all located in Vitoria (Basque Country -Spain-). Altogether they have around 900 employees and are dedicated to the fabrication of all sort of small tools (screws, screwdrivers, spanner, wrench, sockets, double spanner).

The three companies have traditional batch manufacturing environments with fairly simple production situations and formed of general purpose machines.

- DISASTER implementation failure: in 1992, Favahe decided to purchase and implement DISASTER in the three industries (even attended the DISASTER course in USA). However, in the initial data gathering period they realized that they lacked some essential data and a previous step would be the installation of an efficient shop floor control system (MRP was used in that moment only as a capacity planning tool and to generate the purchase and manufacturing orders). Moreover, at the same time DISASTER was bought, they were applying Buffer Management and carrying out an education process on the TOC concepts. As a result of these efforts they realized that with the new control of the shop floor acquired with BM and using their former manual scheduling system, production was able to be efficiently managed without the need of DISASTER.

### 11.6.5 - Overview of DISASTER's users

Despite the recent release to the market of the DISASTER scheduling package, there are some other companies apart from the ones already mentioned that have installed the software or are immersed in the implementation process. However, the lack of reported cases make difficult to assess the extent at which DISASTER is being used and the benefits or criticisms it has received.

Having access to internal Avraham Goldratt Institute -AGI- (DISASTER developers) information, some of the companies in UK and USA that are currently using DISASTER are:

- Bosal: they use DISASTER for strategic planning in several plants.
- BICC: they have problems with buffer sizing.
- CMB: uses the package for strategic planning.
- Brenco: they have reduced WIP by almost 30% using DISASTER's schedules.
- Zycon: they have used the software for constraint identification and "What if"-s. However, the schedules produced are not meaningful for the shop floor.
- Warner Robins Air Force Base -WRAFB-TI-: they have a problem of obtaining the data to load in DISASTER from the many different systems they use.
- ITT: uses the package in two locations.

Further, companies like Baxter, Agfa, P&G (Hamilton), WRAFB-LY, Crown International, and Coshocton Stainless are in the process of implementing the package.

The conclusion that can be drawn from this is that DISASTER, although it has the normal problems of a software that has been recently created, is slowly being accepted in the market and its number of users increases.

## 11.7 - Latest developments in DISASTER

New versions of DISASTER including new features have been developed since the initial Version 1.0.0 released around 1989. The latest developments in DISASTER are:

- Buffer Management: the BM feature was first included in Version 2.0.0 in the middle of 1992. It displays the 'holes' (missing batches) in the time buffers placed in front of the critical parts so that the problem can be solved before causing any damage to the plant throughput.

- Dependent setups: it was included in Version 2.0.1 at the end of 1992, and allows major setups to be saved within a family of products disregarding small setups.

- Multiple resource stations: this feature was also included in Version 2.0.1 and permits workers, tools and machines that are all required to perform an operation on a part be identified to the system and scheduled to work at the same time. This represented a problem when multiple resources worked according to different calendars.

Furthermore, DISASTER's vendors (a) have developed front-end data entry and back-end report generation programs for the package, and (b) use Thinking Process trees to analyze and communicate DISASTER's modelling and implementation issues.

Future planned incorporations to the software are: a windows compatible DISASTER version, alternate resource definition so that automatic offloading can be done in the Drum as an option, fractional WIP quantities inclusion, Calendar output having the text form, and the simultaneous schedule of multiple interactive constraints (in this way, although constraints will still be sequentially identified, 'Fixed Drum Violations' will be avoided in close to balance situations).

## 11.8 - Conclusion

The following remarks can be made related to DISASTER's claims and real capabilities:

» Exaggerated claims: according to DISASTER's vendors, once the three phases of DISASTER are functional, the software should be able to *answer any business question* managers would pose to it. This is a very ambitious aim since managers' concerns include many different areas of the business (e.g. marketing, sales, production, warehousing, shipping, and accounts). The tool that would help them make decisions should comprise enormous data related to all the business disciplines. Kroenke (1989) calls "Organisational Information System" to the system that integrates the activities of different departments into a single business system and that produces coordinated, integrated responses to its environment.

DISASTER is far from being this desired "overall DSS". DISASTER's scope is mainly focused on answering manufacturing questions, and does not contemplate any other department's matters. For example, it will not be able to: (a) include cost analysis while dealing with new equipment investment or comparing the profitability of the schedules produced, (b) deal with product quality matters, (c) contemplate operators skills while assigning jobs, (d) include marketing and maintenance information, etc.. As a result, DISASTER is not capable of answering *any business question* as their vendors claim.

» Poor modelling capabilities: extending the above point, DISASTER's poor modelling capabilities do not permit realistically represent some production situations. As a consequence, many production questions managers may pose to the software will not be answered. Additionally, DISASTER's vendors claim that although some characteristics of the production environment cannot be captured, the appropriate location of time buffers will solve this problem. This appreciation is hard to believe.

However, the modelling capability problem seems to be slowly solved with the development of new features.

» DISASTER's strengths: one of DISASTER's main strengths is its capability to deal with multiple CCRs due to the iterative logic it applies and the fact that individual constraint's Drums cannot be in conflict with each other. Further strengths of DISASTER come from it's 'white box' characteristic and its powerful easy to learn and use interaction capabilities. These two basic features added to the 'What if' facility make DISASTER:

a) A good strategic planning decisions tool: once the three phases of DISASTER are operational, it would definitively be a powerful tool that would enable managers use their intuition while dealing with strategic decisions of production planning. However, DISASTER should not only be used for strategic planning because is by putting the schedules onto the shop floor when the data and the models are cleaned up (otherwise strategic decisions may be based on inaccurate system models).

b) A tool that helps in the development of knowledge: DISASTER's requirement of user's expertise in making scheduling decisions, encourages the sharing of knowledge between the package and the user so that a feasible and 'near' optimum final solution is achieved. This leads to a better understanding of the scheduling problem and a more accurate focusing on the required improvement efforts (POOGI).

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## APPENDIX A: TOC CONCEPTS APPLICATION CASE STUDIES

- Case 1 (Ashcroft 1989)

- Company background: small company that produces kitchen, bedroom and bathroom furniture. They are able to produce a wide range of one-off, highly profitable special products. All the products are made from wood, and the production process involves the conversion of different kinds of rough sawn timber to high quality finished products. Batch production system is utilized. It represents a typical A-plant.

The company operates in very competitive markets regarding mainly to prompt and reliable delivery.

- Initial problems: sometimes large contracts are accepted promising short terms delivery dates in order to remain competitive. These dates are given knowing that in some cases they would invalidate delivery promises on previously accepted orders. The poor due date performance also causes: low management morale, reduced sales motivation, a loss of company credibility, a poor trading reputation, and risks company's long term market position.

- First solution: batches were grouped in order to allocate work to particular machines in the factory and increase utilization. Each batch was planned to take 3 weeks from the start of manufacture to dispatch.

- Further problems: large batches production gave rise to: erratic raw material demand and production process flow, delays in starting and completion of works, high WIP, expediting, and overtime. This are typical problems caused by employing machine utilization as a performance measure.

- Further typical solutions: the above problems give often the misleading impression that the maximum throughput had been reached. The solutions normally taken in this case are: expand capacity, repositioning of machinery, rent of additional storage space, and acquisition of computer-based PPC systems.

- TOC application: TOC philosophy was applied in the following phases : (1) identifying the major bottlenecks (analysing the workloads implied by different order book profiles), (2) reducing the batch sizes, (3) educating the workforce in the new TOC principles, and (4) applying a manual DBR scheduling system.

- TOC application results: as a result of these changes: throughput increased, inventory decreased (75% WIP reduction and 50% raw materials reduction), worker morale increased, and the job satisfaction was improved. Furthermore, customer service was improved as a result of high quality products and reduced production lead times (from an average of 4 weeks to 7 working days).

■ Case 2 (Colvenaer et.al. 1992)

- Company background: the company is part of a large Belgium multinational and they transform large rolls of plastic sheet into small sized final sheets. The production process is quite complex and contains a high degree of uncertainty in some processes. The manufacturing process is typical of a V-plant and employs a push logic to manage production.

- New company aims: a few years ago management aimed to achieve a smooth flow by reducing overall inventories. Kanban application was discouraged because it would result in large trim losses. After reading "The Goal", it was decided that its ideas could bring the answer.

- Applying TOC: the first step was to identify the CCR. This was a difficult task, on one hand, because the plant was quite balanced and the CCR seemed to shift depending on the product mix, and on the other hand, because of the way people were assigned to machine groups (depending on the number of shifts the machine would be a bottleneck or not). The bottleneck was finally identified with the aid of a simulation package based on technical machine specifications, average product mixes, and demand.

The second step was to define the constraint buffer. Then, effort was focused on reducing production lead times and variance. WIP was reduced introducing quality inspections in the three shifts (in the past, the lack of inspection in the night's shift made material accumulate), and lead times decreased when the order generation administrative procedures were changed.

- Final results: as a consequence of TOC application, inventory levels were reduced in a factor of 60% and production lead times also decreased considerably.

On the other hand, the CCR has now moved to another process and the company is facing major workforce education problems due to machines utilization performance measures applied for many years.

■ Case 3 (Callahan 1989)

General Motors (GM) in Windsor, Ontario, introduced TOC ideas with JIT concepts to form what they called "synchronous manufacturing" approach. Synchronous manufacturing implementation began in 1986, at which time the company was achieving 17.3 inventory turns per year. By December 1988 the plant had achieved 50.4 inventory turns. The company also achieved 94% reduction in lead time and a $23 million reduction in annual costs, while increasing output by 16.8%.

■ Case 4 (Fogarty and Blackstone 1991)

AT&T microelectronics division in Reading applied what they call "common sense manufacturing". This approach is described as including a pull system, strategic buffer locations, constraint management, DBR scheduling, and total employee involvement. It seems like a mix of JIT and TOC concepts. The results reported include a 50% reduction in inventory, 70% reduction in lead time, 60% increase in rework, and a five-fold increase in turnover.

■ Case 5 (Koziol 1988, Reimer 1991)

- Company background: the company is Valmont/ALS, a batch type steel fabricator in Brenham, Texas. The plant manufactures tapered steel poles in heights from 20 to more than 200 feet according to customer specifications. The industry should be considered capital intensive, and they apply standard cost, MRP scheduling and labour reporting systems. There are 40 manufacturing cost centres, each with burden rates set for labour, variable expense, and fixed expense.

- Problems: they suffer from the "end of the month syndrome", the production flow is described as chaotic, and expediting and overtime are employed to solve the scheduling conflicts. This scenario resulted in: tense emotions, low productivity, inadequate machinery, equipment breakdowns, bad scheduling, and high absenteeism.

- Applying TOC: in 1986 the division president distributed copies of "The Goal" to all the staff. Discussing the book, they came to the conclusion that they were facing a market constraint. They decided to apply TOC ideas in the following order: (1) batch sizes were reduced by approximately 40% (with this action production flow experienced less disruption), (2) the CCR was identified, (3) constraint buffers were set, and (4) DBR was applied.

The major obstacles they encountered were: (a) the hard reeducation process required, and (b) decide how to schedule the shop floor in a most effective manner.

- Final results: by the end of the year, the improvements obtained with DBR were: lead times for certain products were cut in half, due date performance improved to the mid-to-upper 90%, shipment levels increased to the highest levels in the company history, and overtime was kept to reasonable levels. Throughput increased without rising operating expense and inventories were reduced.

- ■ Case 6 (Reid and Thompson 1992)

Kanban was replaced by DBR in the assembly operation at Hewlett Packard's Microwave Division in Scotland. The JIT system was set up in 1984 and worked reasonably well in the first few years. At that time assembly's excess capacity and overtime were applied to "catch back" any shortfall in production due to equipment breakdown, employee absence or material shortage. However, as JIT uses similar daily rates to regulate the material flow, when factory output increased, the company struggled to maintain the fixed daily rates. They faced large order fluctuations, frequent equipment breakdowns and shortages of material.

As a consequence of these problems and after reading "The Goal" and "The Race", they decided to apply DBR to reduce material shortage and protect assembly from production disturbances. The first step (as the constraint was identified -assembly- and the daily orders represented the Drum) was to decide the time the parts required to reach assembly from gating operations (Buffer). The Rope was established and all intermediate operation's Kanbans were eliminated.

Inventory level increased in front to the assembly operation, but this lead to throughput increase by protecting assembly from production disturbances. Besides, increased flexibility was achieved with minimal increase in WIP.

- ■ Case 7 (Spencer 1994)

Trane Company's Commercial Systems factory in Macon, GA, produces large self-contained air conditioner units for buildings in an assembly line fashion.

The PPC system they used was a combination of MRP, JIT and TOC. The MRP system (as a data collector and integration tool) provided a framework for the TOC and JIT methods. In 1988 the following JIT concepts were applied: levelled MPS, production schedule linearity, scheduled preventive maintenance, multiskilled employees, plant layout revision to accommodate JIT, and Kanban to replenish sub-assemblies to final assembly.

In 1989, the factory implemented the following TOC concepts: inventory and operating expenses for internal management decisions, TOC 5 focusing steps (used by management to provide a process for making continuous improvements to the production process), TP, and DBR and BM at the shop floor level.

When DBR and BM replaced Kanban, the average units produced per day increased from 3 to 6 with the same workforce. Dramatic lead time reduction was the reason for that output increase.

In 1992, as a result of the profitability analysis performed using the TOC operational measures, two new product lines were installed, that traditional cost accounting valuation methods did not justify. This company still uses a dual-accounting system, with external reports generated by the accounting module of MRP, and internal management reports based on TOC's operating and financial measures.

■ Case 8

- Company background: Copreci S.Coop. is a medium size company -900 employees- located in Aretxabaleta (Basque Country -Spain-) and forms part of the Mondragon Cooperatives Group (more 25000 employees). It manufactures 9 families of different products divided in the same number of independent automated production lines: washing machine plastic valves, cooker valves, washing machine programmers, rod devices for dishwashers and fridges, cook transformers, etc..

Each product family normally contains more than 3-4 operations previous to a final assembly and no more than 4-5 different products can be manufactured in the same line. All the raw material, purchase products and final products are stocked in a big central store.

- Problems in the past: in 1989, they used MRP/MRP-II's push logic to schedule and track the orders. The push logic and the use of extra payments based on productivities (incentives), led to high WIP and a difficult to control production system. An additional problem were the long setup times required in some production lines (up to 6 hours in some cases). As a consequence, production lead times were about 4 weeks.

- New production control and scheduling systems: in 1989, the Production Director read "The Goal" and suggested to read it to the rest of the managers. They thought that the TOC ideas could bring some benefits to the production control and scheduling tasks and decided to apply them. The CCR was identified (in all the production lines the constraint was the final assembly), and DBR technique installed: every week a schedule for the final assembly operations is created based on customer requirements (Drum). Everyday, the scheduler sends a list of the required material for next day fabrication and assembly (8 hours Time Buffer). As their Production Director maintains, they also perform Buffer Management because every morning -before fabrication- the foremen check the availability of raw material in the adequate places painted in blue and investigate the causes for the missing products.

- Benefits obtained: with the application of the SMED techniques to reduce setup times, and the utilization of DBR -with their particular BM- (a) WIP has been greatly reduced, (b) actual production lead times are less than two weeks (from the former 4 weeks), and (c) customer service has improved.

- Future projects: Copreci is thinking of integrating ORTHENS scheduling software with their actual MRP/MRP-II and BULL systems to obtain the product mixes that would allow a smooth and fast production flow. They also came across of DISASTER, however they decided that the data accuracy and continual data maintenance it required was a bigger burden than the benefits they could obtain from it.

■ Case 9

- Company background: Heasa of Vitoria (Basque Country -Spain-) is one of the many companies of the area dedicated to produce tool kit components (screwdrivers, wrenches, spanners, etc..).

It has 300 employees and their manufacturing process is a complex batch manufacturing system with general purpose machines and functional layout. They differentiate two main areas in the plant: forging (that is the initial operation that feeds the whole plant) and the rest (intermediate operations, heat treatment and final operation). There is a big raw material store next to the forging process and small intermediate buffers located in strategic places containing the products processed in forging.

- Problems in the past: in the past they used the MRP/MRP-II system to create the purchase and manufacturing orders. However, all the common customer forging parts were grouped together in a single order. Then, when the material of this order went to succeeding operations there was a problem of determining the accurate number of parts required for each customer (material "stealing" was a normal practice).

- New production control system: at the end of 1993 they installed a particular Buffer Management application:

a) In all the intermediate inventory buffers there is a board divided in three different sections and with different colours at each of them: green> released orders, yellow> orders with 5 days to due date, red> late orders.

b) Everyday, production planning sends to each departments foremen a manufacturing order confirmation (for individual customer orders) and a material requirement stick.

c) The foremen locate the material stick in the appropriate place in the buffer board.

d) The operators, guided by the information in the board take the material from the buffers and produce the products with earlier due date and in the sequence that is marked in the board.

e) Everyday, the foremen checks the due dates of the materials in the board, locates them in their appropriate area, and analyze the reasons for the missing material.

With this relatively new production control system they feel they have started to solve the past material "stealing" problems.

## APPENDIX - B: PRODUCTION LINE OPERATING BEHAVIOUR PRINCIPLES

*** Aims of the production line study**

The investigation of the operational behaviour of a production line under many different production situations has two aims:

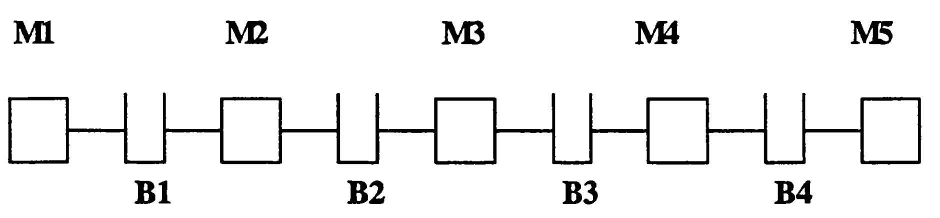
1- To gain the necessary insights about the performance of the system (in terms of throughput, inventory, production lead time, resources utilization, etc..) when different circumstances take place in the modelled environment (e.g. when buffers are located in specific places, or when the process times are subject to different variability, or when the machines are unreliable, etc..).

2- To examine the way the Drum-Buffer-Rope scheduling logic addresses particular operation line behaviour attributes.

*** Production line**

A <u>production line</u> (flow line, or tandem queuing system) is a series arrangement of process stages, where each stage can be formed of one operation station or several identical facilities organised in parallel. Jobs pass through all the stages in the same sequence, thus material handling is automated and simplified but limiting greatly the flexibility of the system. Production management and control is a relatively easy task and high product volumes can be produced economically.

Production lines are formed by service stations or machines (M1, M2, M3,...., Mk) normally separated by "k-1" inventory banks/ buffer storages (B1, B2,...., Bk-1). Material flows from outside the system to M1, then passes to B1, then to M2, and so forth until it reaches Mk and leaves the line.



*** Production line behaviour definitions and features**

The following definitions will help understand production line behaviour:

» Processing time/cycle time: is the sum of the time to transfer the part from the previous station and the time required to process the part at the station.

» Repair time: this begins when a breakdown is observed or maintenance begins, and ends when the station becomes ready to begin processing.

» Operating time or time between breakdowns: is the time from the instant when the station becomes ready to begin processing following repair until the instant when the next station breakdown occurs. The line is said to be up if the last station is working and down if the last station is stopped.

+ Production line efficiency

Production line efficiency measures the reliability of the system. It can be defined as (Buzacott 1967) "the ratio of what the system actually produces in some given time to what the system would have produced in the same time if no station had stopped".

If the production line were fully synchronized and production disturbances would not exist, line efficiency would be 100% and throughput would not be lost. However, statistical fluctuations and unpredictable events do exist and reduce line efficiency by causing the following phenomena:

■ blocking and starvation situations: a station is said to be blocked if the service of the item in the facility cannot get out of it because of the downstream buffer being full or the next station being down. In this case, the station remains idle until the next station is in service again. On the other hand, a station is starved if it has no items to process, either because the upstream buffer is empty or the machine that feeds it is down.

+ Line efficiency increase factors

The production rate -efficiency- of the line can be increased by:

» Reducing the processing time of the stations (increase machine production rate): processing time reduction implies decreasing the time to transfer the item from one station to the other and the time to perform the operation.

» Increase machine efficiency by:

1- Reducing the breakdowns frequency.

2- Reducing the duration of the breakdowns (decreasing the repair time).

» Reduce the frequency and duration of the unsynchronized, disruptive events: decrease the inherent line randomness -processing time, breakdowns, and repair- that cause machines to be blocked and starved.

» Reduce the machines set-up times: engineering efforts could be focused on providing standardized tool changers or particular devices for each machine and set-up requirement.

» Reduce the impact of production disturbances by employing inventory buffers: this is the main method employed to lower the effects of disruptive events. With buffer stocks, stations can continue working even if one of them goes down (dependency is broken/the line is decoupled), and blockages and starvation cases are notable reduced.

Without buffers, unless workstations are synchronized and are not subject to variability, they will interfere with each other and total line production capacity will be lost. Thus, as long as it is assumed that certain inventory in the system can bring some benefits, the next normal step is to determine the minimum buffer capacity required and the best way of allocate it along the line.

*** Production line study**

+ Production line performance measures and objectives

The typical performance measures employed in of production lines' analysis are: average production rate (also called throughput, flow rate, or efficiency), average WIP, average lead time, machine idle/busy time, mean waiting time. Other can be: quality of output, number of early/tardy jobs, proportion of early/tardy jobs, mean lateness, maximum lateness, output cost, and customer service.

The scope of the production line study is normally related to balanced/synchronized, unbalanced, and unsynchronized lines. The features normally analyzed in the different production situations are: length of the line, buffer capacity, buffer allocation (equal/levelled and unequal buffer allocation), unreliable workstation (location, effects deterministic and random breakdowns, and effects of deterministic and variable repair times), and CCRs influence in the production line.

+ Analytical versus simulation models

Analytical models describe the system using mathematical or symbolic relationships. The analytical techniques normally employed are: queuing models, Markov chain analysis, and unconstrained non-linear programming. These techniques are used to derive a formula or define an algorithm by which the performance measures of the line can be calculated. However, for large scheduling problems it is not possible, within a reasonable amount of computer time or space, to obtain the results. In those cases, further assumptions have to be made to limit the behaviour of the system that results in the production of an approximate model rather than an exact one.

Simulation, on the other hand, require the definition of the state of the system's variables and the procedure or rule that cause this variables change over time. As the values of the variables change, the system moves from state to state. Simulation is then the process of moving the systems from state to state according to the rules that define the operational procedure of the system.

+ WITNESS simulation software

WITNESS simulation package will be utilized in the production line behaviour study to create and analyze the models under different production situations. All the simulations are runned for at least 30000 seconds -after reaching a steady state- to obtain reliable results.

WITNESS is a graphical interactive simulation tool with Artificial Intelligence features that enables represent actual operations by creating a picture of the flow of parts trough the various work centres. WITNESS combines the power of moving colour graphics with user interaction to permit the modeller see the system operation, and interactively use "what if" techniques to investigate, plan, and implement changes.

*** Production line behaviour principles**

The line behaviour attributes under different production situations are given the name of "principles". This principles, obtained from many author's research work and investigated by simulation, are reviewed in the following sections (a final Table summarizes all of them).

### 1 - Balanced and unbuffered lines with equal process time variability

A line is considered balanced when all the stations have the same average processing time -although they can have different variability-. The situation studied here is a serial line formed of a single product, without any buffer stocks between the stations, and free of breakdowns. In the first principle, even process times are considered deterministic:

> **Principle - 1:** the output rate of a reliable balanced deterministic line is the production rate of any of the stations of the line.

As long as it is assumed that the line is totally reliable and that processing times are deterministic, there is no possibility for disturbances to take place (this is not totally true if we include for example set up of handling times). Without unpredictable events, the production rate of the line is the production rate of any of its stations.

When process times are subject to equal variability, the following principles would take place:

> **Principle - 2** (Conway et.al., 1988; Owen and Mileham, 1991): variability in process times causes blockage and starvation that diminishes the line output (Model 1).

Longer than 'normal' process times -due to variability- can originate the stoppage of the upstream and downstream machines (the machine following the one with a longer than average process time will be starved, and the preceding machine will have its output blocked). Blockages and starvation interfere with each other and originate a loss in the line output. However, as can be seen in the following formulas, the real output loss is less than the one calculated analytically due to the "absorbing" effect of blockages and starvation windows (to accommodate to the formulas, instead of including different process times variability, different down time frequencies are employed -but with the same mean down time as in the model, 10%-):

1) Owen and Mileham (1991): R -> Repair time, N -> Number of machines, B -> Interbreakdown time, and C -> cycle time.

$$E = (1 - (R \times N)/(B \times C)) \times 100$$

2) Gershwin (1994): T -> Total run time, *m -> Total number of failures, 1/r -> Repair time.

$$E = ((T - (m/r)) / T) \times 100$$

3) Gershwin (1994): T -> Total run time, N -> Number of machines, m -> number of failures at each station, and R -> Repair time.

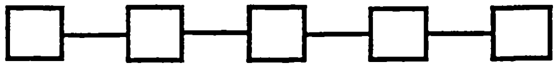
$$E = ((T - (N \times m \times R)) / T) \times 100$$

The down times utilized to validate principle 2 are: B=10/R=1; B=5/R=0.5; B=2.5/R=0.125. While the total run time (T) is 30000. The result of the three analytical cases, was a line efficiency of 50%. On the other hand, utilizing the simulation package line efficiency is about 91%. Owen and Mileham (1991) demonstrate that the theoretical output give a straight line graph that diminish sharply with the line length. This results, as in our case, does not match with the results obtained by the simulation model. The reason for this is that starvation windows moving down the line absorb the blocking effects that move in opposite direction.

**Principle - 3** (Owen and Mileham, 1991): the time lost due to blockage and starvation is approximately the same along the line and arise in opposite direction (Model 1).

The time lost in blockages and starvation is almost the same and "move" in opposite direction. This is because, although the last machine can never be blocked, the preceding machine can be blocked by the last machine, and the one preceding this one can be blocked by the two downstream ones, -and so on-. So the time lost due to blockages increases "backwards", with the first machine loosing more time due to blockages than the others. Starvation effect occur just the same but in opposite direction.

**MODEL - 1**

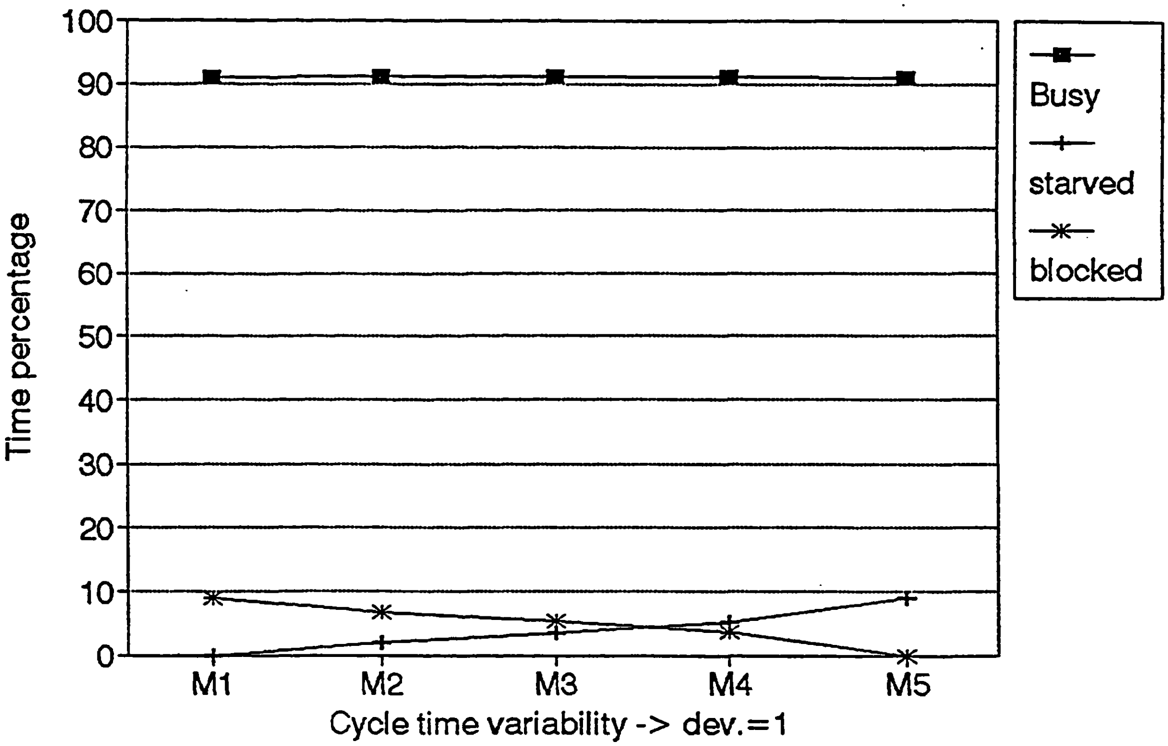


**C=NORMAL (1,0.1)**

**Same process time (C)> Normal Distribution (mean=1, dev.=0.1)**

# BALANCED UNBUFFERED LINE

(Busy, blocked, and starved times)



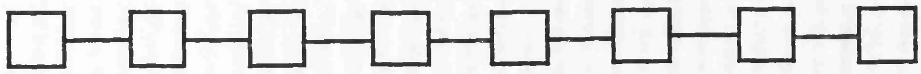
**Principle - 4** (Conway et.al. 1988; Owen and Mileham 1991): the smaller the process time variability, the higher the line production rate (Model 2).

As processing time variability constraints the achievement of a synchronized and smooth production flow, the bigger the variability, the higher the interference between stations (more time lost due to blockages and starvation), and the lower the final output.

**Principle - 5** (Conway et.al. 1988; Gershwin, 1994): line efficiency loss occur in the first few stations. If further machines are added to the line, the efficiency loss does not increase accordingly (Model 3).

Increasing the number of machines in the line (assuming they have he same processing time variability pattern), the production rate of the line decreases apparently to a non-zero limit (Gershwin, 1994). But it is demonstrated that most of the efficiency loss occur in the first machines (Conway et.al. maintain that the loss happen in the first 5 machines). Additional machines do not affect output in the same manner.

MODEL - 2

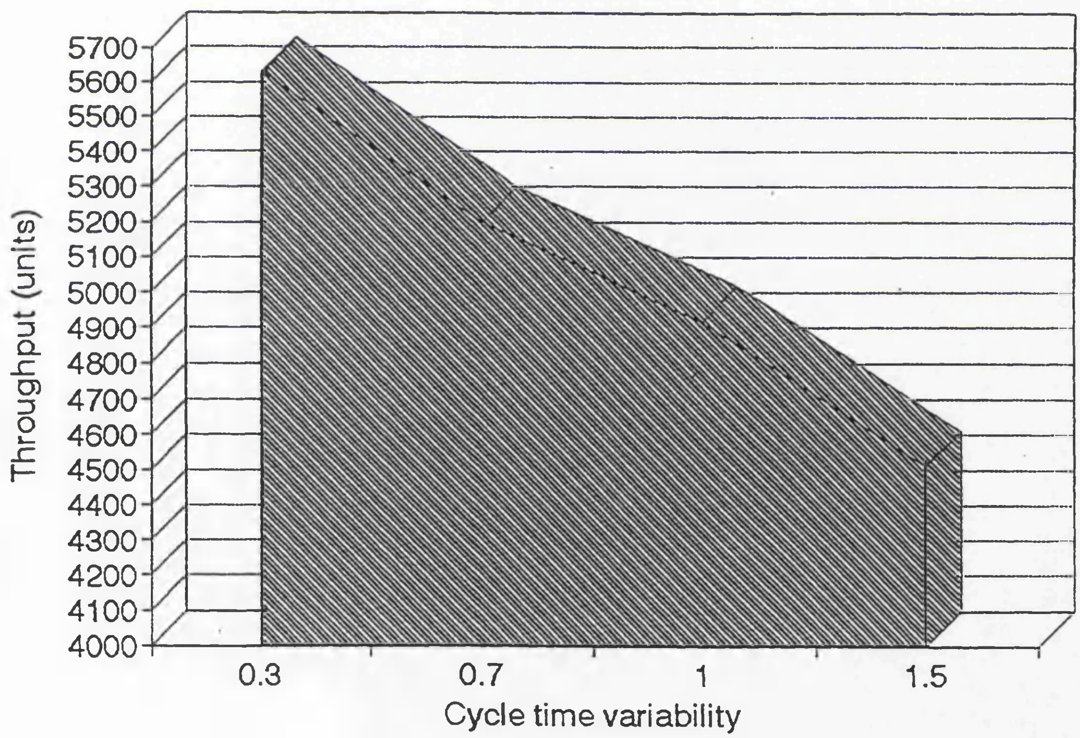


C=NORMAL (5,dev)

Case A> dev.=0.3
Case B> dev.=0.7
Case C> dev.=1
Case D> dev.=1.5

# BALANCED UNBUFFERED LINE

(Output)

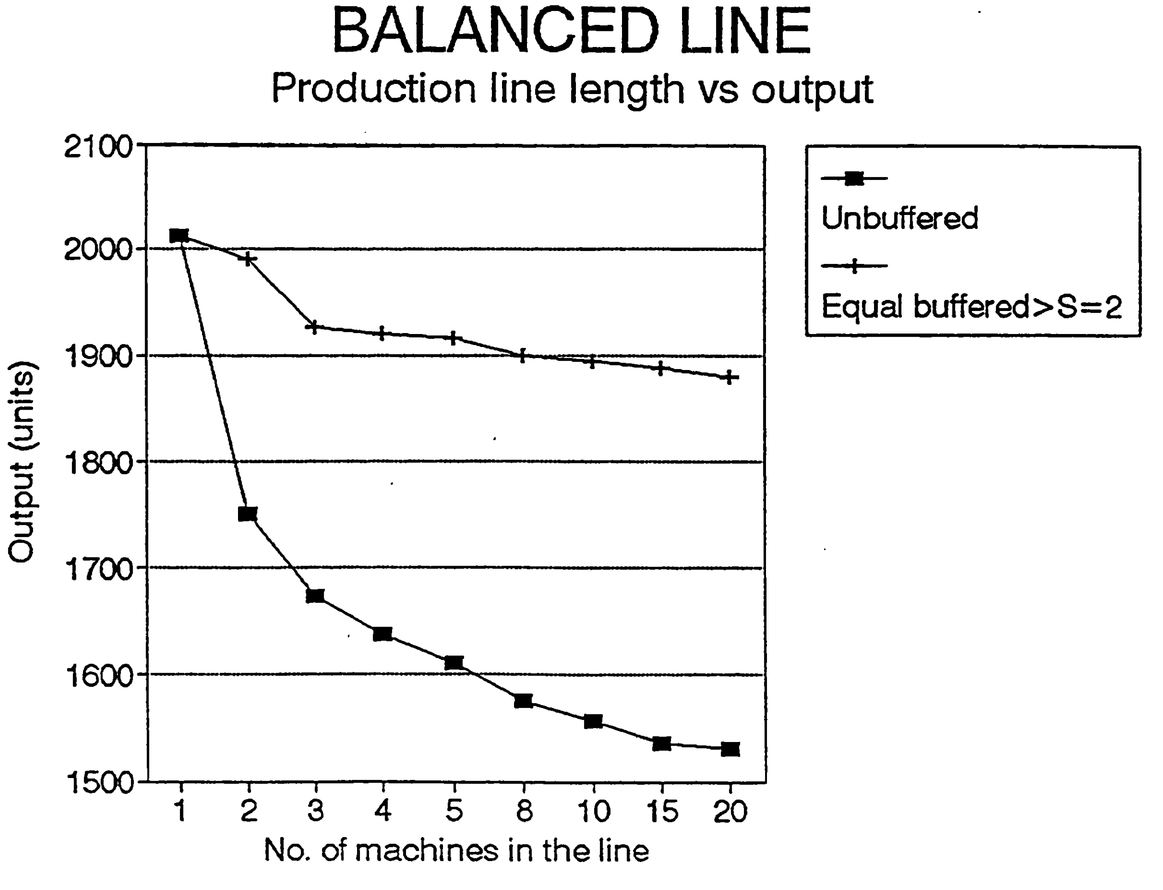


## MODEL - 3

This model shows how line efficiency decreases as new machines are added to the line (4,5,8,10,15,20). However, it also demonstrates that most of the output loss occur in the first 8 stations; while throughput diminishes in a lower degree when new stations are added to the line.

The model has also been runned placing buffers of 2 units between all the stations, and the outcome is that the major output loss occur in the first 3 stations; diminishing considerably with the new added stations.

The process time employed has Normal distribution with a mean time of 5 seconds and a deviation of 1 second.



**2 - Equal buffered balanced lines with the same process time variability**

In this situation it is assumed that the there is equal amount of finite buffer stocks distributed between all the stations and that process time variability is still the same for all the stations. In this case -and also in the following situations-, the above 2, 3, 4, and 5 principles can also be applied (their validity is demonstrated by authors like: Dalley and Gershwin, 1992; Gershwin, 1987; Lambrecht and Segaert, 1990). The following principles are related to this particular production situation:

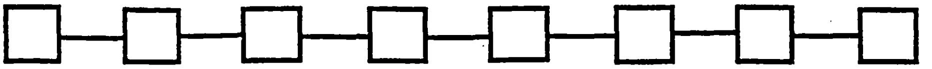
> **Principle - 6** (Buzacott, 1967; Conway et.al., 1988): buffer capacity should be proportional to the coefficient of variation of the process times (Model 4).

The frequency blocking and starvation occur is related to the variability of process times at the adjacent workstations. Similarly, the power of WIP buffers to alleviate this problems depends on the variability amplitude. Conway et.al. (1988) demonstrate that buffer capacity equal to 10 times the coefficient of variation recovers 80 to 85% of the capacity lost due to fluctuations.

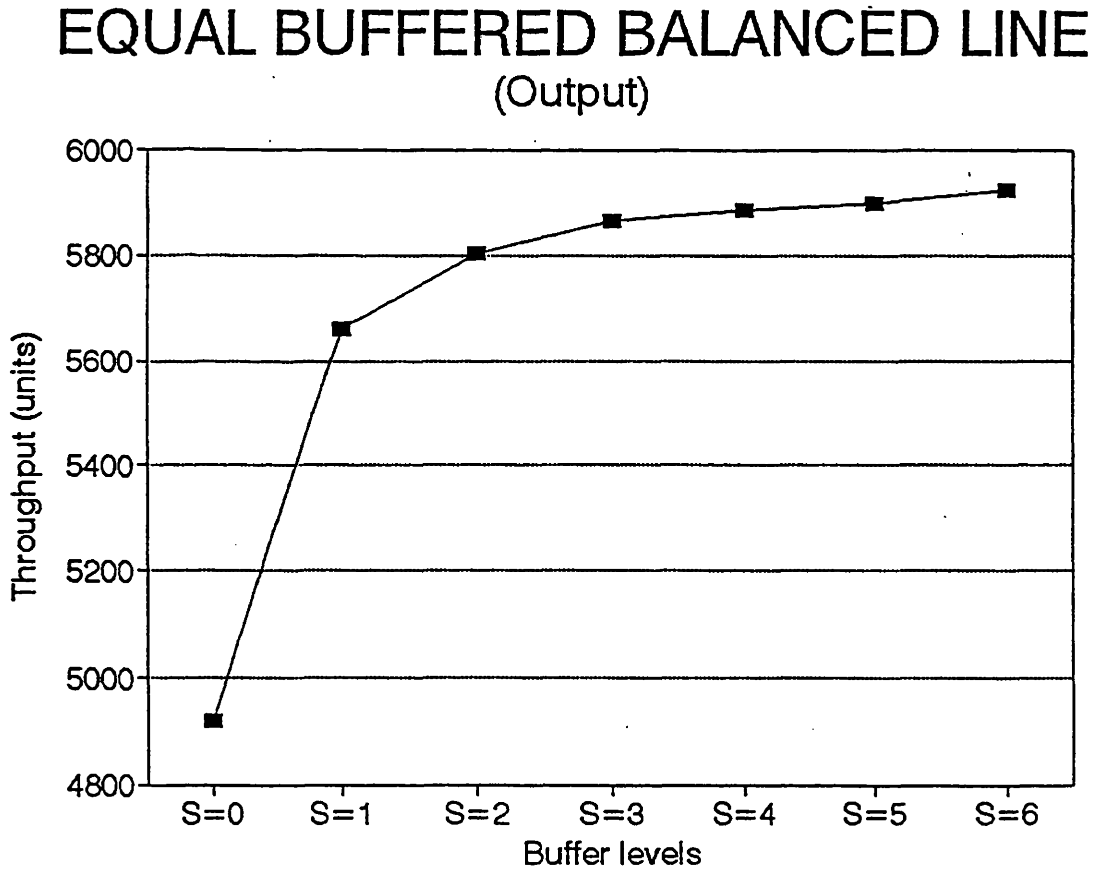
> **Principle - 7** (Buzacott, 1967; Conway et.al., 1988): line output improvement obtained by the utilization of buffer stocks diminish as the capacity of the buffers increases (Model 4).

Although at the beginning the provision of more buffer capacity normally brings notable benefits in terms of increased output rate, when the capacity of the buffers increases notably, diminishing returns arise very quickly (concave function). These last two principles can generally be applied in all the situations.

**MODEL - 4**



**C=NORMAL (5,1)**
**Different buffer sizes (S>0,1,2,3,4,5,6)**

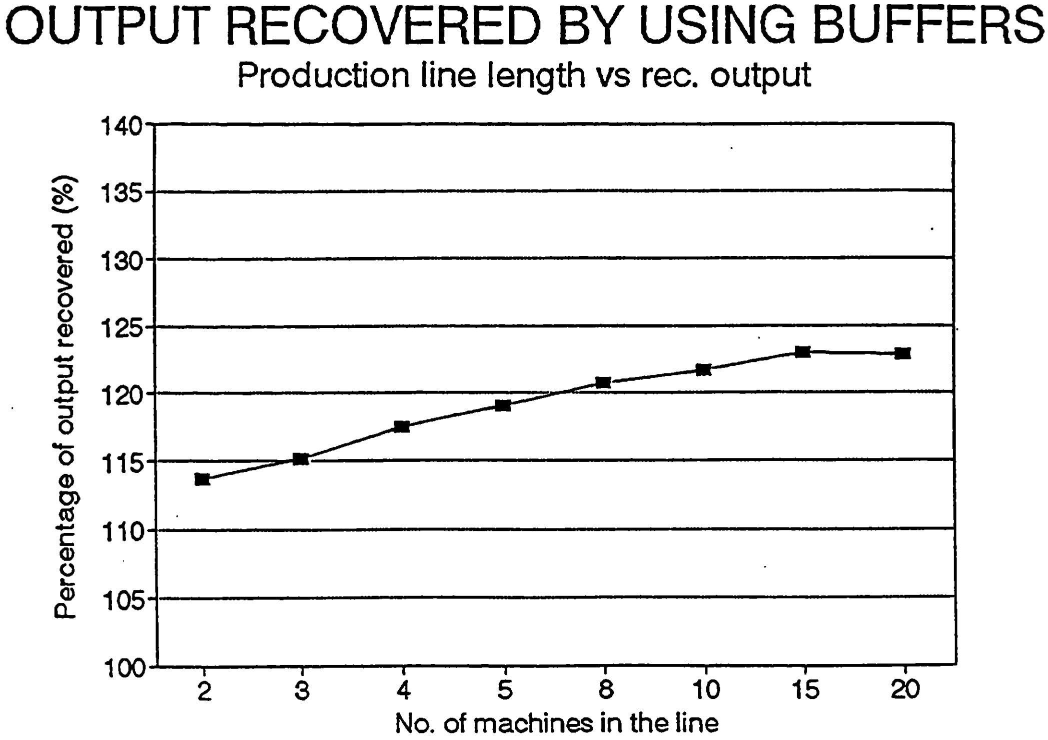


**Principle - 8** (Conway et.al., 1988): The production line capacity recovered by equal buffering is nearly independent of the number of stations and of the process time distribution (Model 5).

Conway et.al. tried to find an empirical relationship between line length, buffer size, and different process times. After many experimental runs they realize that the relationship between the buffer size and the fractional recovery of lost capacity was independent of the number of stations and the form of the process time distribution.

Model 5 tries to demonstrate this principle. However, from the results obtained, the output percentage recovered by using a buffer of 2 units increases as the size of the line increases. Therefore, principle 8 can be questioned.

**MODEL - 5**



**Principle - 9** (Conway et.al., 1988; Gershwin, 1987, 1994; Lambrecht and Segaert, 1990): the average buffer content decreases as we progress down the line (Model 6).

The reason for this is that as we progress down the line, blocking becomes less common and starving occurs more often, so each successive buffer has less content. This is a general principle valid for most of the situations concerned with balanced lines.

**Principle - 10** (Gershwin, 1987): symmetry and complementarity > in symmetric lines, the level of one buffer is complementary to the level of the buffer just in the opposite position of the line (Model 6).

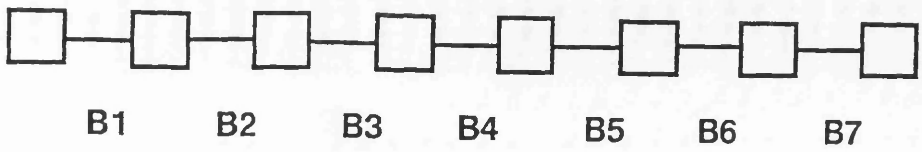
For example, if the line is formed by 20 workstations and all buffers' capacity is 10, the buffer content in the third position (B3) will be complementary to the one in the 17-th position (B17). Applying principles 9 and 10 the following conclusions can be expressed:

» B3+B17=10

» B3>B17

» B10=5 (the buffer in the middle is half full on average, regardless of the process times distribution).

MODEL - 6

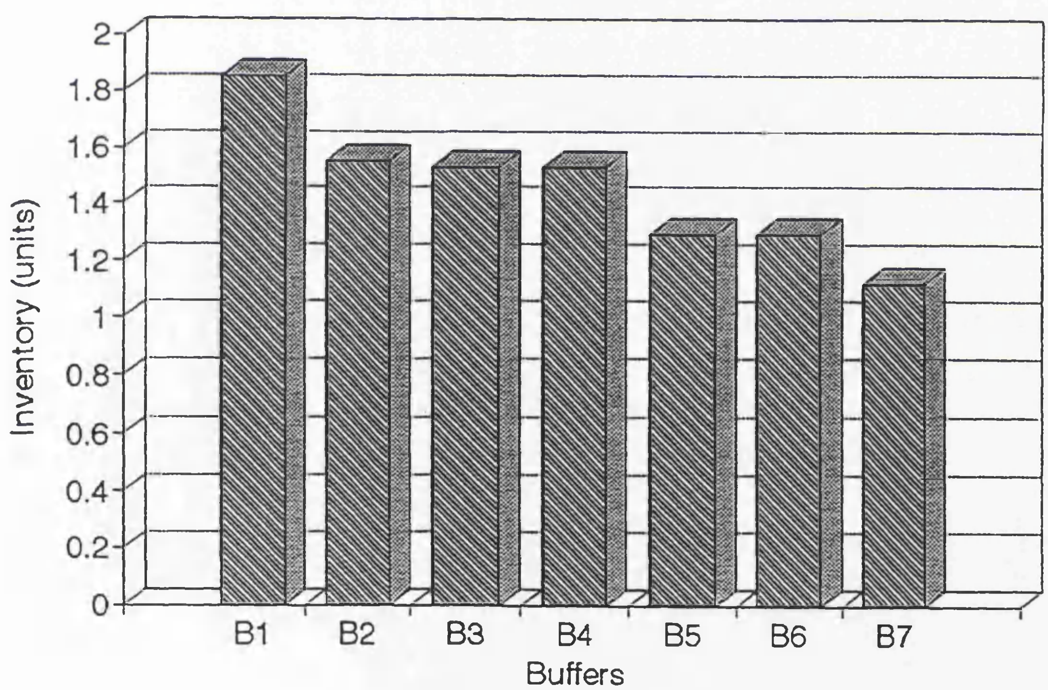



C=NORMAL (5,1)

Buffer capacity between all the resources (S)=3

# EQUAL BUFFERED BALANCED LINE

(Buffer levels)



### 3 - Unequal buffered balanced lines with equal process time variability

Assuming that the average process times are still the same and contain the same variability pattern, in this case there are a limited number of space buffers available (the capacity of the buffers is not equal). The problem in this case is normally to allocate the available buffers in the best possible way. The principles related to this situation are:

**Principle - 11** (Buzacott, 1967; Conway et.al., 1988; Gershwin and Shick, 1983; Gershwin, 1987, 1994; Lambrecht and Segaert, 1990; Owen and Mileham, 1993): Allocate buffer capacity as nearly equally as possible.

The reason for this is that buffers divide the line in smaller parts (decouple the stations by breaking dependency) and absorb the spread of the production disturbances. Thus, when the line is formed of identical stations, all of them have to be equally decoupled in order to achieve maximum output.

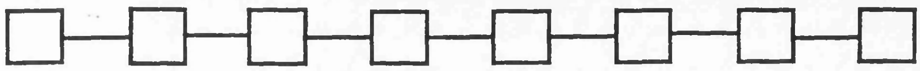
**Principle - 12** (Conway et.al., 1988; Gershwin, 1987; Hillier and Boling, 1979; Lambrecht and Segaert, 1990): if equal buffer allocation is not possible, the best buffer allocation pattern is symmetrical with slightly greater buffer capacity in the centre (centre-weighted spread).

As buffers decouple the effects of disruptions from one part of the line to the other; then the best way to divide the line is in two halves. Otherwise, unpredictable events would be more intense in the longer line and would affect total production output in a higher degree.

**Principle - 13** (Conway et.al., 1988; Gershwin, 1987): reversibility: the same production capacity is achieved with mirror image buffer allocations even though the buffer content distribution is not the same (Model 7).

For example, the efficiency of a four machine balanced line is the same with a buffer allocation pattern of 4-3-3 or of 3-4-4. Despite this, whenever possible, symmetrical allocation is preferable for lines with identical stations than asymmetrical allocation.

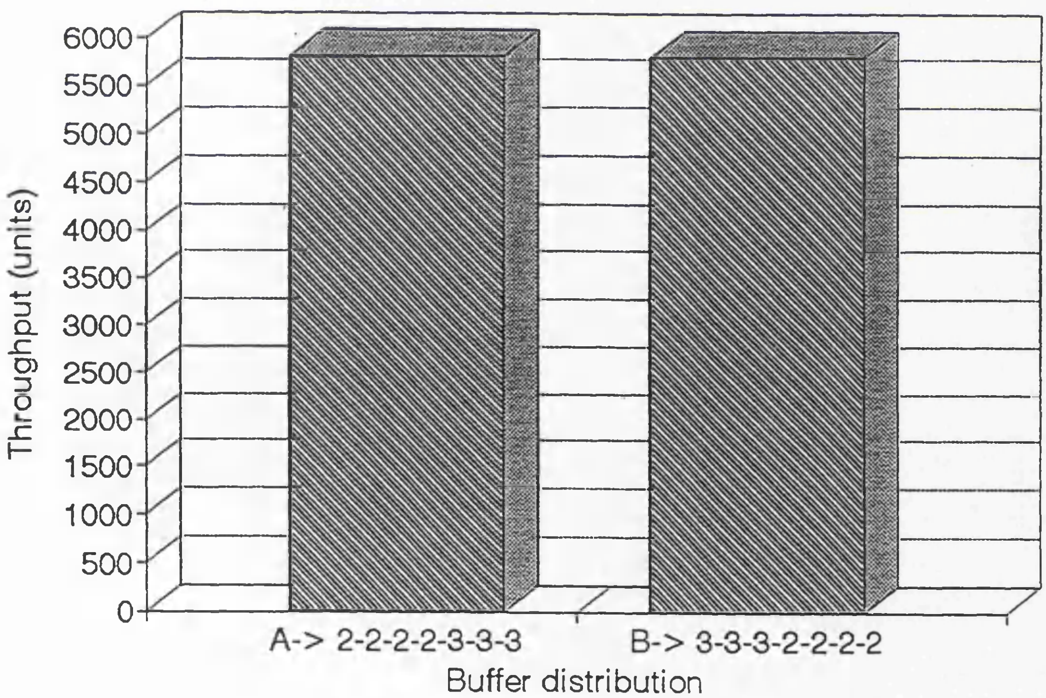
MODEL - 7



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Buff. distr. A> | 2 | 2 | 2 | 2 | 3 | 3 | 3 |
| Buff. distr. B> | 3 | 3 | 3 | 2 | 2 | 2 | 2 |

C=NORMAL (5,1)

# UNEQUAL BUFFERED BALANCED LINE
(Output)



**4 - Unequal buffered balanced lines with different process time variability**

This situation arises when all the stations in the line have equal mean process time, but the standard deviation of the process times may be different at each station. The typical problem in this case is also to find the best buffer allocation pattern to achieve maximum production output.

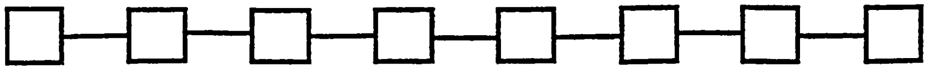
**Principle - 14** (Conway et.al., 1988): symmetric process time variability distribution requires symmetric buffer capacity allocation.

When the variability of the process times is symmetrically distributed, buffers should also be symmetrically allocated. Besides, principle 10 can also be applied in this case: the average level of corresponding buffers in the line is complementary.

**Principle - 15** (Conway et.al., 1988): asymmetric process time variability distribution requires asymmetric buffer capacity allocation with more buffer capacity placed near the more variable station (Model 8).

Workstations with large process time variability should have larger buffers for both input and output. In this way, the major source of disruptions is "isolated" from the rest of the system and the spread of production disturbances is absorbed by the buffers.

## MODEL - 8

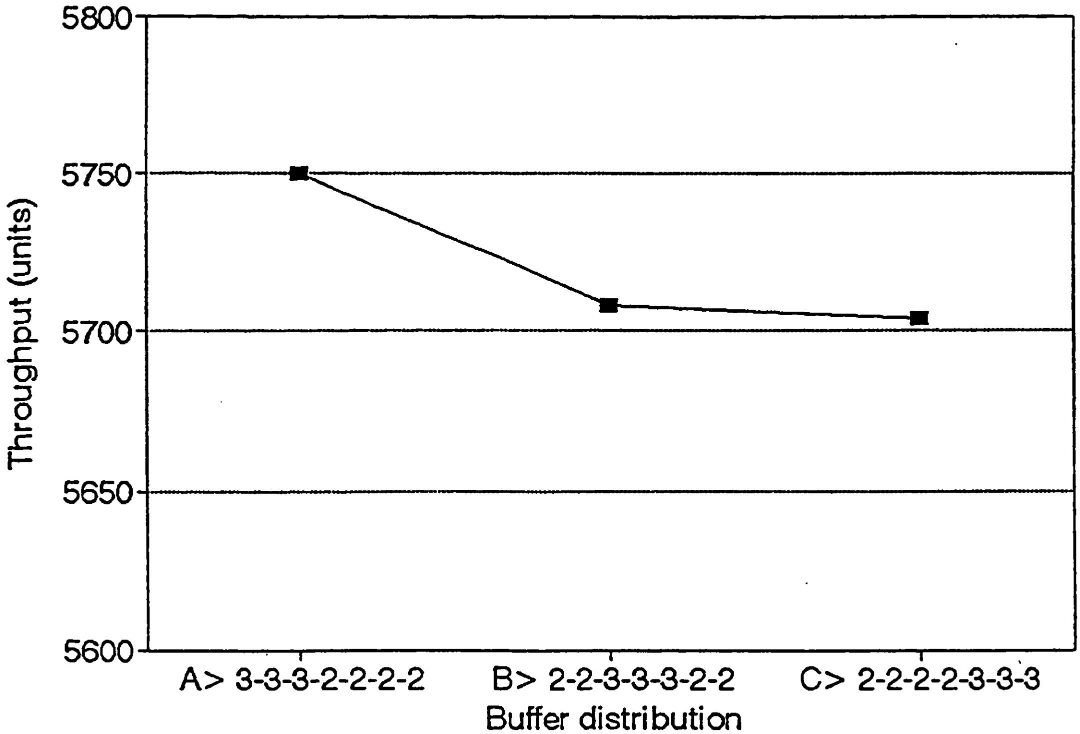


| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Buff. distr. A> | 3 | 3 | 3 | 2 | 2 | 2 | 2 |
| Buff. distr. B> | 2 | 2 | 3 | 3 | 3 | 2 | 2 |
| Buff. distr. C> | 2 | 2 | 2 | 2 | 3 | 3 | 3 |

C=NORMAL (5,1)

# BALANCED LINE WITH UNEQUAL VAR.

(Output)



**5 - Unbalanced lines**

Unbalanced production lines contain one or more stations with different mean process time (the one with the higher process time is the capacity constraint resource of the system -CCRs-). This case occur more commonly in real flow lines in which perfect balance can be hardly achieved. The following principles are related to unbalanced lines:

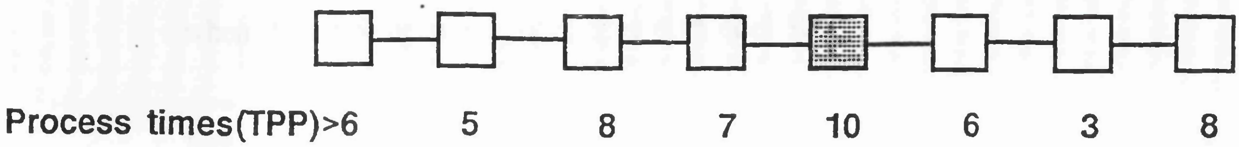
**Principle - 16** (Buzacott, 1968; Conway et.al., 1988; Dalley and Gershwin, 1992; Glassey and Hong, 1993; Lambrecht and Segaert, 1990): The production rate of the machine with less relative capacity (CCR) is the maximum attainable output of the line (Model 9).

Logically, the capacity of the line will never exceed the capacity of the CCR, and in the best of the cases (when disturbances do not reduce line's efficiency) line's output rate will equal CCR's production rate.

**Principle - 17** (Conway et.al., 1988; Lambrecht and Segaert, 1990): The CCR should have buffers surrounding it, and the buffer capacity should be proportional to the difference between the CCR's process time and the process times of the rest of the machines.

This principle is the consequence of principles 6 and 15. In those cases, it was explained that there must be a relation between the degree of the disturbances and the capacity of the buffers placed to lower their effects. In addition, buffers should be placed before and after the CCR, otherwise it can suffer from starvation or blockage.

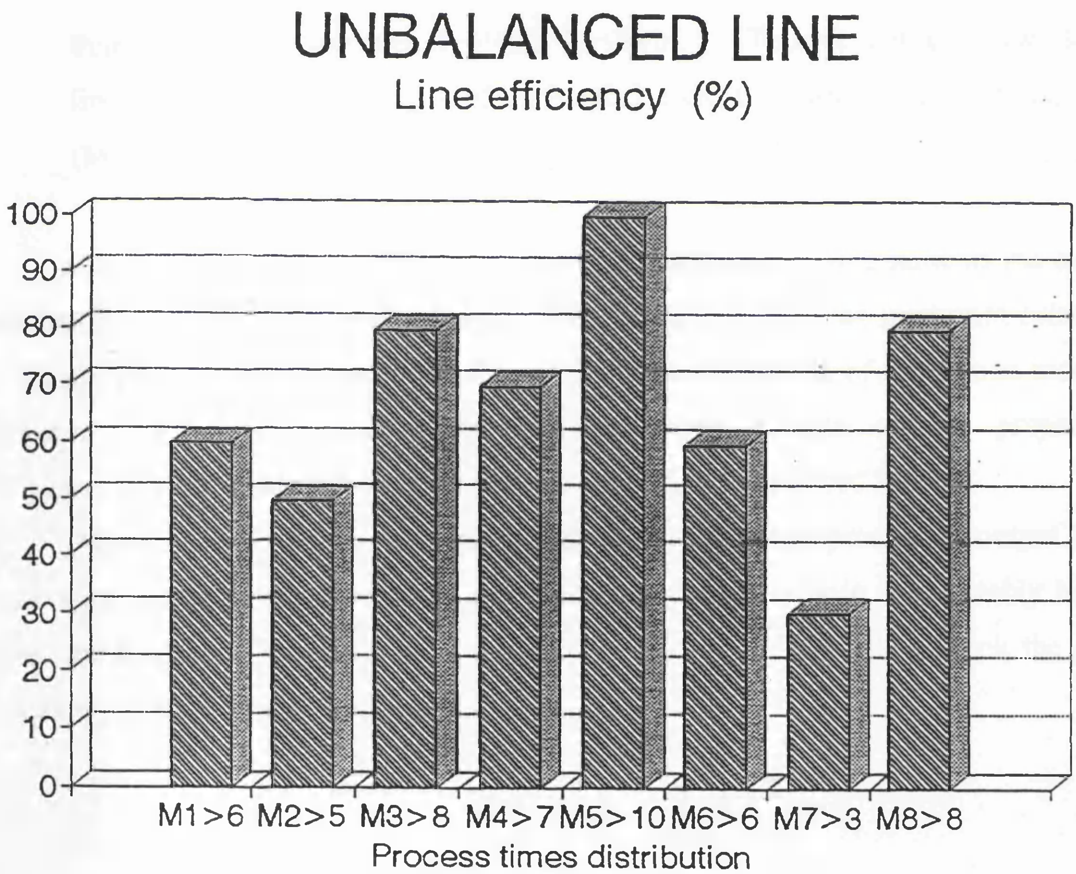
MODEL - 9




C=NORMAL (TPP,1)

C=NEGEXP (TPP)

S> any buffer capacity



**Principle - 18** (Conway et.al., 1988; Dalley and Gershwin, 1992; Gershwin, 1994; Lambrecht and Segaert, 1990): buffer capacity is substantially reduced when the CCR becomes more severe (Model 10).

Intuitively it can be seen that the CCR will pull the buffer capacity towards itself. The input buffer will tend to be full -or will increase without bound in the case of unlimited buffers-, and the output buffer will tend to be empty; but a reasonable buffer capacity is needed in order to avoid starvation and blockage. With a severe CCR (significant difference between the processing time of the CCR and the processing times of the rest of machines) the inherent excess capacity of adjacent stations will make them process the item before the CCR, and the CCR will hardly ever be blocked or starved. Thus, buffers to be effective require a line be close to balance.

**Principle - 19** (Conway et.al, 1988; Gershwin, 1987): reversibility > two serial lines that are mirror images of each other have the same production capacity (Model 11).

The output obtained with one process time distribution is the same as the output obtained just with the reverse distribution. Whether or not this is an important principle in the design stage of the line, it is of great benefit in the design of simulation models. Moreover, as a consequence of the reversibility and complementarity properties, principles 9, 13, 14, and 15 can perfectly be applied to unbalanced lines.

Model 11 validates this principle and shows that although production output is the same with the two reverse process time distributions, inventory is considerably higher when the longer process times are placed at the end of the line (they block the parts processed in the previous resources).

MODEL - 10

Process times(TPP)>6 5 8 7 CCR 6 3 8

Non-CCRs> C=NORMAL(TPP,1)

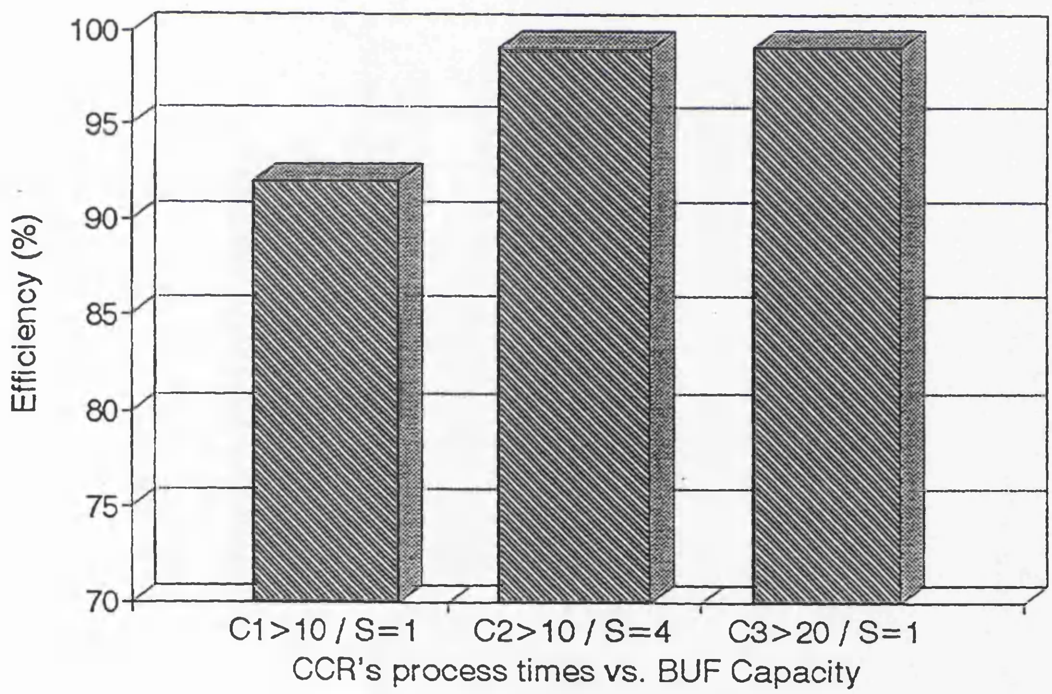
Case A: CCR > C=NEGEXP(10) / S=1 (between all resources)

Case B: CCR > C=NEGEXP(10) / S=4 (between all resources)

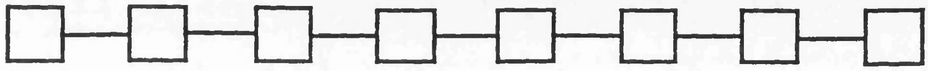
Case C: CCR > C=NEGEXP(20) / S=1 (between all resources)

## UNBALANCED LINE

Line efficiency (CCR => NEGEXP)



## MODEL - 11

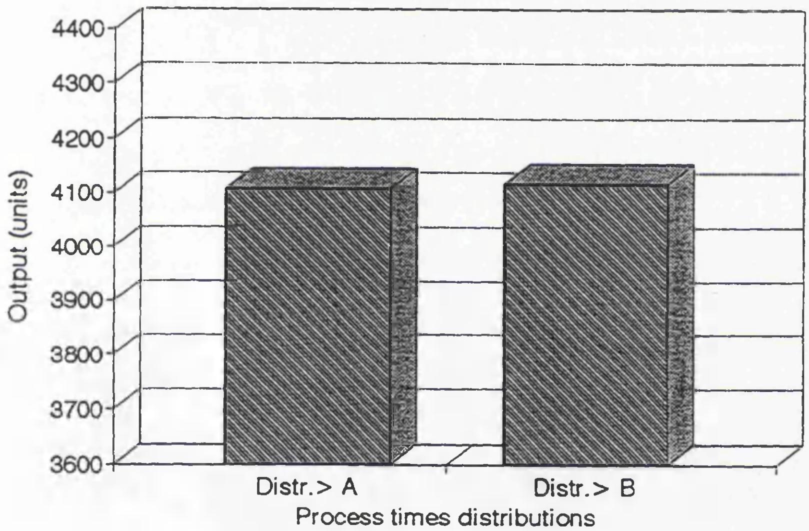


| Process times | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Distr. A (TPP)> | 6 | 6 | 7 | 5 | 4 | 4 | 5 | 3 |
| Distr. B (TPP)> | 3 | 5 | 4 | 4 | 5 | 7 | 6 | 6 |

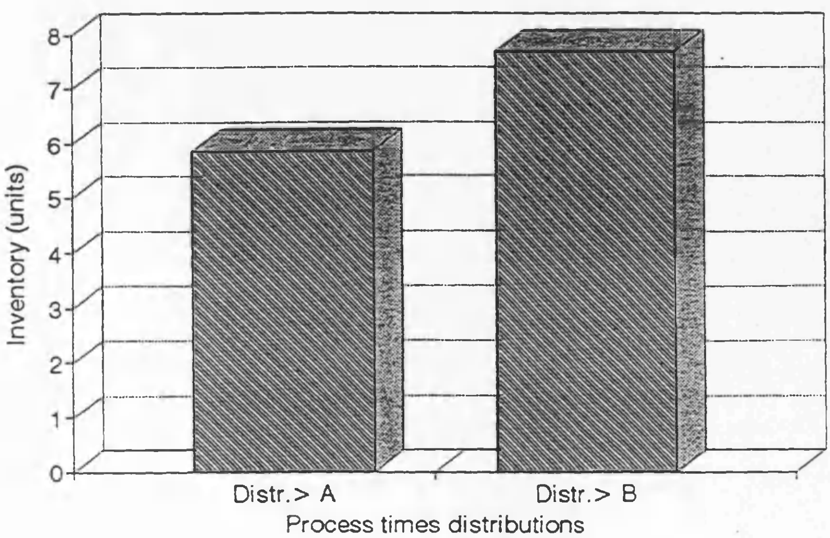
**C=NORMAL (TPP,1)**

# UNBALANCED LINE

(Output)




(Inventory)



### 6 - Unreliable stations

When a workstation goes out of service due to failure of equipment or tool breakdown, the effect is the same as lengthening the process time of the part currently in process by the time required to repair the station. The resulting process time is extremely variable because failures are unpredictable and causes substantial delays when they occur.

Related to former principles, if equal machine breakdown distribution along the line is assumed, principles 5, 9, 11, 12 ,13 can be straightforwardly applied. On the other hand, the following ones require a slight change in the terms:

» Principle-4: the more frequent the production breakdowns, the higher the production output.

» Principle-6/7: There is a buffer capacity limit above which buffer has no marginal value. This buffer capacity is given by the ratio of average repair time to average processing time.

Similarly, when the same down percentage takes place, but the frequency distribution vary from one station to another, principles 14 and 15 can be applied -with minor changes-. Finally, when the machines of the line have different down times (the more common situation in reality), the workstation with the longer time out of service will act as the CCR, and principles 16, 17, 18, and 19 can then be applied.

Further principles related to unreliable production lines are:

**Principle - 20** (Buzacott, 1970): if either repair times or times between breakdowns are random, similar buffer capacities are needed to achieve a given increase in production output.

**Principle - 21** (Buzacott, 1970): if both repair times and times between breakdowns are random, the buffer capacity required to produce a given capacity increase is double the capacity required when only repair times or times between breakdowns are random.

Conway et.al. (1988) maintain that for random failures and constant repair times, buffer capacities formed by the ratio between repair time and the process time will regain about 50% of the output lost to interference between stations. Doubling that buffer capacity, the gain is about 70%.

**Principle - 22** (Gershwin, 1983): production output remains approximately constant when repair and breakdown probabilities are multiplied by a number & and the buffer capacities are divided by &.

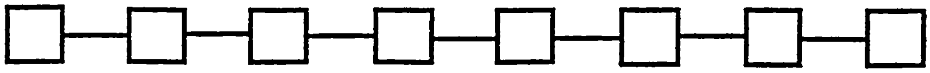
**7 - Bowl phenomenon**

The "bowl phenomenon" refers to the increase in the production rate obtained by unbalancing purposely the line. The different forms in which this phenomenon can appear are:

**Principle - 23** (Lambrecht and Segaert, 1990): improvements in line performance can be achieved if the stations with more variable process times are positioned at both ends of the line (Model 12).

# MODEL - 12

Process times variability (dev.)



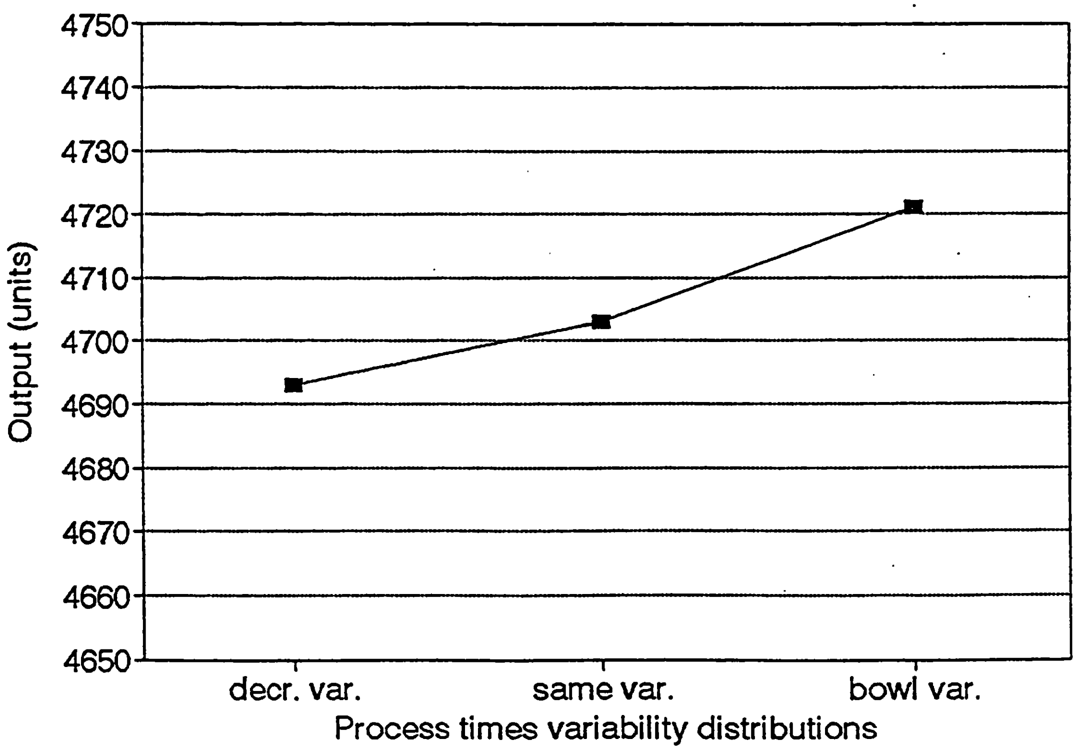
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Decr. var.(dev.)> | 2.8 | 2.7 | 2.6 | 2.55 | 2.45 | 2.4 | 2.3 | 2.2 |
| Same var.(dev.)> | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| Bowl var.(dev.)> | 3 | 2.7 | 2.3 | 2 | 2 | 2.3 | 2.7 | 3 |

C=NORMAL(10,dev.)

S=0

## PRODUCTION LINE WITH "C" VARIABILITY

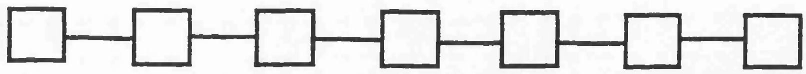
Output vs diff. variability distr.



**Principle - 24** (Dalley and Gershwin, 1992): production output increases when the inner part of the line is more reliable than the outer part (Model 13).

**MODEL - 13**

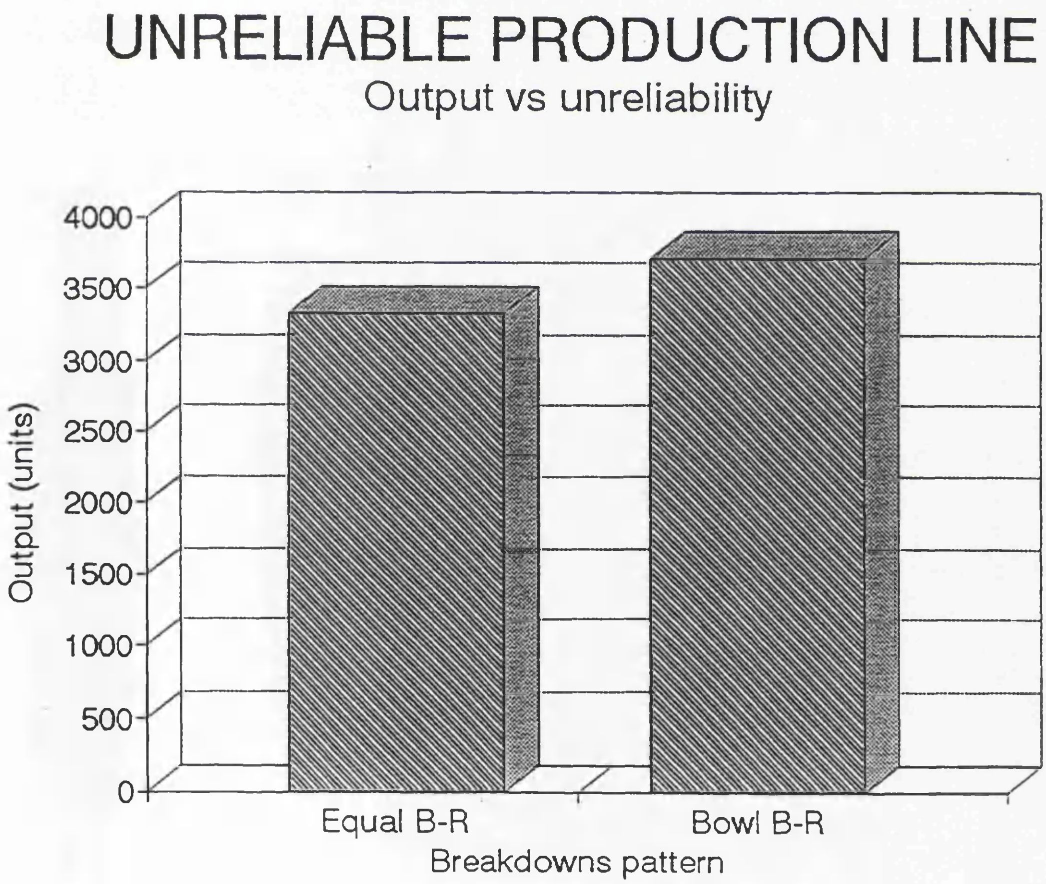
Breakdown distr. (B-R)



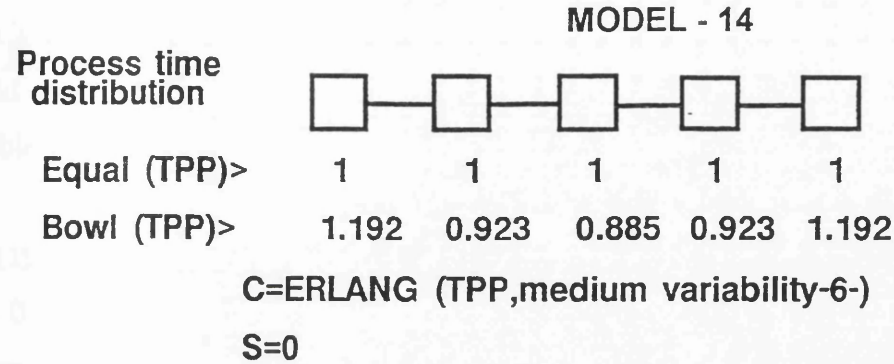
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Equal B-R | B> | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | R> | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Bowl B-R | B> | 3.5 | 4 | 4.5 | 5 | 4.5 | 4 | 3.5 |
| | R> | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

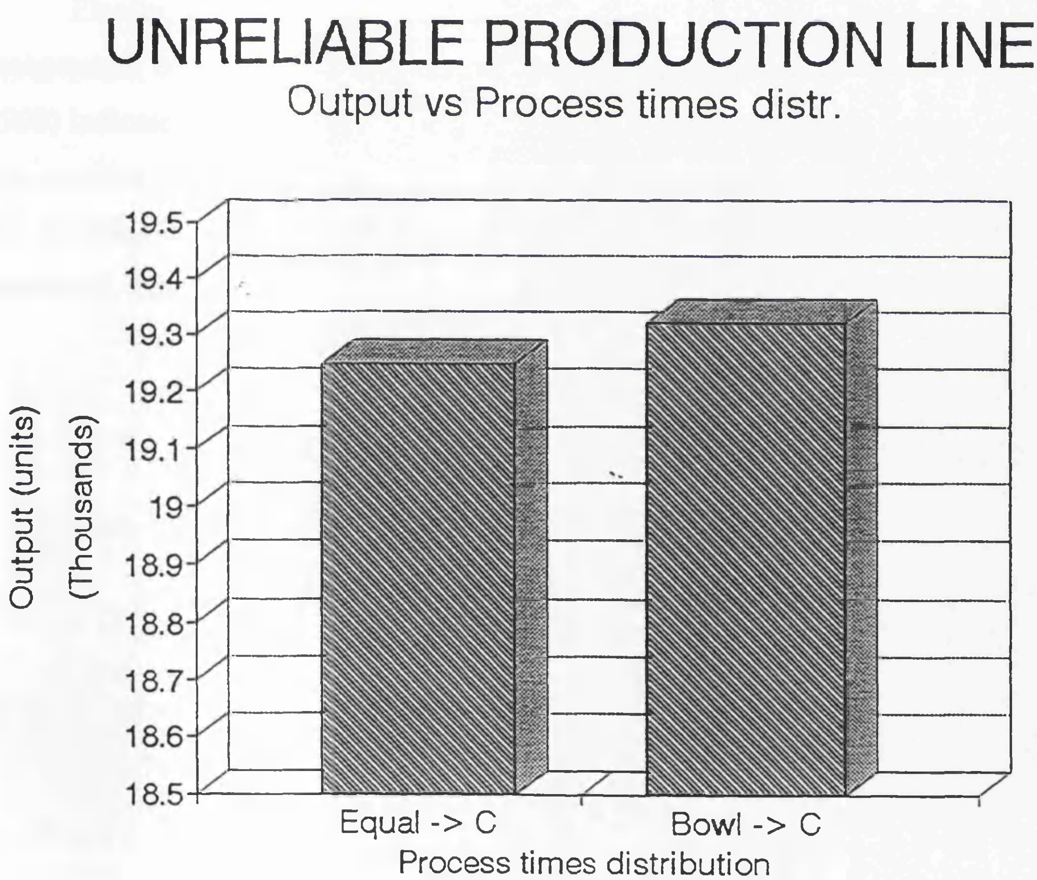
C=1 (deterministic)

S=0



**Principle** - 25 (Hillier and Boling, 1979): production output is increased when the greatest amount of work -longer process time- is allocated in the stations at the ends of the line and the least amounts of work in the stations of the middle (Model 14).



**Principle - 26** (Dalley and Gershwin, 1992; Gershwin, 1987): more buffer capacity should be allocated in the middle of the line than in the end of it.

This principle correlates with principle 12.

**Principle - 27** (Rao, 1976): variability imbalance > work load -process time- should sometimes be transferred from the more variable stations to the less variable ones.

Rao (1976) maintains that when the coefficients of variation of the process times are less than 0.5, the bowl phenomenon should be applied; otherwise, higher production output can be achieved with what he calls "variability imbalance". This phenomenon proclaim an "inverted bowl" solution by which production rates can increase about 6.5%.

Finally, Hillier and Boling (1979) demonstrate that the gain obtained by the bowl phenomenon over equal distribution is usually less than 1%; and Dalley and Gershwin (1992) indicate that *the reason for the bowl shape being better, is the assumption that the first machine is never starved and the last machine is never blocked*. In real systems, the first machine is occasionally starved and the last machine is blocked during temporary declines in demand.

| | PRODUCTION LINE OPERATIONAL BEHAVIOUR PRINCIPLES |
|---|---|
| BALANCED AND UNBUFFERED LINES WITH EQUAL PROCESS TIME VARIABILITY | 1- The output rate of a reliable deterministic line is the production rate of any of the stations of the line.<br>2- Variability in process times causes blockage and starvation that diminishes the line output.<br>3- The time lost due to blockage and starvation is approximately the same along the line and arise in opposite direction.<br>4- The smaller the process time variability, the higher the line production rate.<br>5- Line efficiency loss occur in the first few stations. If further machines are added to the line, the efficiency loss does not increase accordingly. |
| EQUAL BUFFERED BALANCED LINES WITH THE SAME PROCESS TIME VARIABILITY | 6- Buffer capacity should be proportional to the coefficient of variation of the process times.<br>7- Line output improvement obtained by the utilization of buffer stocks diminish as the capacity of the buffers increases.<br>8- The production line capacity recovered by equal buffering is nearly independent of the number of stations and of the process time distribution.<br>9- The average buffer content decreases as we progress down the line.<br>10- Symmetry and complementarity: in symmetric lines, the level of one buffer is complementary to the level of the buffer just in the opposite position of the line. |
| UNEQUAL BUFFERED BALANCED LINES WITH EQUAL PROCESS TIME VARIABILITY | 11- Allocate buffer capacity as nearly equally as possible.<br>12- If equal buffer allocation is not possible, the best buffer allocation pattern is symmetrical with slightly greater buffer capacity in the centre (centre-weighted spread).<br>13- Reversibility: the same production capacity is achieved with mirror image buffer allocations even though the buffer content distribution is not the same. |
| UNEQUAL BUFFERED BALANCED LINES WITH DIFFERENT PROCESS TIMES VARIABILITY | 14- Symmetric process time variability distribution requires symmetric buffer capacity allocation.<br>15- Asymmetric process time variability distribution requires asymmetric buffer capacity allocation with more buffer capacity placed near the more variable station. |
| UNBALANCED LINES | 16- The production rate of the machine with less relative capacity (CCR) is the maximum attainable output of the line.<br>17- The CCR should have buffers surrounding it and the buffer capacity should be proportional to the difference between the CCR's process time and the process times of the rest of the machines.<br>18- Buffer capacity is substantially reduced when the CCR becomes more severe.<br>19- Reversibility: two serial lines that are mirror images of each other have the same production capacity. |
| UNRELIABLE STATIONS | 20- If either repair times or times between breakdowns are random, similar buffer capacities are needed to achieve a given increase in production output.<br>21- If both repair times and times between breakdowns are random, the buffer capacity required to produce a given capacity increase is double the capacity required when only repair times or times between breakdowns are random.<br>22- Production output remains approximately constant when repair and breakdown probabilities are multiplied by a number & and the buffer capacities are divided by &. |

## APPENDIX C: OPT SOFTWARE IMPLEMENTATION CASE STUDIES

* <u>Successful OPT implementations</u>

In the following Table are summarized some of the many successful OPT implementations (including comments about the company background, OPT features, and final results).

| 1- COMPANY<br>2- PRODUCT<br>3- ENVIRONM. | INITIAL PROBLEMS (GENERAL COMMENTS) | COMMENTS ABOUT OPT | OPT RESULTS |
|---|---|---|---|
| <u>CASE 1</u> (Jones and Roberts 1990)<br>1- Perkins Engines (Peterborough's plant)<br>2- High quality diesel engines.<br>3- High variety in the manufacturing process. | » They aimed an inventory reduction and thus generate cash.<br>» Pilot scheme: a jobbing shop and a flow line.<br>» Stock recording was an OPT requirement.<br>» MRP-II has a gross rather concept of time. | » Some data needs difficult to supply (stock data).<br>» Vital to have accurate data about bottlenecks.<br>» Accurate information and maintenance of the BOM and routings.<br>» Is not user friendly and requires time to learn.<br>» It has considerable potential and numerous facilities.<br>» It is run several times (changing the variables) (simulation capability).<br>» It takes 9 hours to create a schedule (data collection, data feeding, and running).<br>» Education at all levels is required. | » Payback period of 3-4 months.<br>» Inventory reduction of 40%.<br>» Inventory turns increased from 4 to 10.<br>» Throughput increased by 60%.<br>» Shortages have been reduced.<br>» All levels of personnel think more closely of what they are doing and why. |

| | | | |
|---|---|---|---|
| CASE 2 (Dwyer 1990)<br>1- Fenner<br>2- Mechanical power transmission equipment<br>3- ? | | » The data about constraints needs to be precise. | » On the first OPT run the company lost 10% production output.<br>» After 6 months average production doubled.<br>» Workforce worried about the lack of WIP and the increased number of setup due to the small batches.<br>» OPT useful as a longer term planning tool. |
| CASE 3 (Dwyer 1990)<br>1- HiTemp (Fareham and South Molton)<br>2- Precision aerospace components<br>3- (Traditional batch manufacturing system) | » Machine tools, factory layout and MRP system were all geared to large batches.<br>» Wandering bottlenecks appeared caused by constant product changes. | » Bottlenecks were identified.<br>» OPT recommended to tie all batch production directly to the order book (run very small batches > long set ups). | » After cutting the planning horizon, Throughput increased 30% and lead times were reduced from 3 months to 4 weeks.<br>» "OPT works but only if you believe in it". "..it affects the entire organization"...and require appraise, and train at all levels. |
| CASE 4 (Bond 1993)<br>1- ?<br>2- Basic components from bought-out castings.<br>3- Conventional machine shop of 60 machines. No assembly. Simple linear chain. | » The company aims to keep shelf stock of all main catalogue items. | » They aim to anticipate problems ('What if' tool).<br>» 2 hours running the process to expire alternatives (time consuming)<br>» Thorough education and accuracy of data were required for its implementation.<br>» Conditions to make OPT work:<br>1- Operators must obey OPT schedules. 2- Product machine layout is required. 3- Operators must be multiskilled. | » No regular planning meetings. All the work is carried out by the detailed schedule.<br>» Absenteeism has been reduced.<br>» Operators understand the relationship between their own work and the throughput of the factory.<br>» OPT as a simulation tool.<br>» Reduced WIP. |

| | | | |
|---|---|---|---|
| CASE 5 (Kerpchin 1990)<br>1- Tri Industries (U.S.)<br>2- Engine parts to the US aerospace industry.<br>3- Multiple and different processes (difficult scheduling task) | » The former MRP system could not keep up with demands. | » It conformed to the defense contractor requirements: modular BOM and alternate routes.<br>» Strong support from the vendor.<br>» Simulation capability due to the finite forward scheduling nature.<br>» Good report capabilities.<br>» 7 months of implementation: training, "cleaning" the data, adjusting schedules, and finding the bottleneck(s). | » Immediate benefits: improved due date performance and reduced lead times.<br>» Sales increased 13%.<br>» Inventories dropped 35%. |
| CASE 6 (Jones and Roberts 1990)<br>1- Textron Aerostructures<br>2- Aircraft producer<br>3- ? | » Overwhelmed with rapid growth projections and out-of-date manufacturing control system<br>» A more efficient scheduling system was required to tackle the increased product demand. It should comprise:<br>1- Short implementation time.<br>2- Short pay back period. | » It took only 4 weeks to load OPT and interface it with in-house files.<br>» There was no extensive rewriting of BOM and routings.<br>» Training and internal managers' expertise contributed to ease the implementation.<br>» 45 year old work philosophy was changed with OPT introduction.<br>» Company wide acceptance had to take place to succeed with OPT. | » Short implementation period.<br>» In 6 months they were gaining pay back on their investment with visible results.<br>» Shortages and delays of the critical parts were cut in half.<br>» WIP was reduced by 28%.<br>» Lead time was reduced from 16 weeks to 20 days. |
| CASE 7 (Jones and Roberts 1990)<br>1- Allied Automotive Bendix Friction Materials Division (Troy/New York)<br>2- Drum brake linings, cerametalics, and resin products.<br>3- ? | » It must provide quality parts with on-time deliveries to a highly demanding and fluctuating market. | » OPT was chosen mainly because of its philosophy of operating with low inventory.<br>» They installed FOCUS to translate the daily OPT reports to their IBM data base system.<br>» OPT helps them pinpoint production build up problems before they happen.<br>» Their initial aim of a smooth flow was not totally achieved due to a constant incorporation of new processes, machine down times, vendor delivery problems, and tooling shortages. | » In the first year of installing OPT inventory was cut in half.<br>» In a few years of operation with OPT the inventory turns increased from 8-9 to 12. 4 years after this they have 15.<br>» Lead times were reduced from 5 weeks to 2 weeks. |

| | | | |
|---|---|---|---|
| <u>CASE 8</u><br>(Bylinsky 1983)<br>1- GE, Wilmington (North Carolina)<br>2- Aircraft-engine parts plant<br>3- ? | » They want to reduce inventories in half in one year time | » Goldratt claims that is possible to reduce inventory more than 50% only in 3 months if the suppliers cooperate.<br>» Plant's executives consider Goldratt unrealistic and decide to maintain a safety inventory. | » In one year operating with OPT they cut inventory by $30 million and saved about $2 million in carrying costs. |
| <u>CASE 9</u> (Jones and Roberts 1990)<br>1- Bendix France.<br>2- Wide range of automobile components.<br>3- ? | » On-time supplies are the major concern.<br>» Flow limits had peaked and MRP was installed to provide an original computer controlled data base.<br>» "The MRP system told us the what but not the why". | » A month of rigorous training and 6 months of implementation were required. | » Stock turns increased from 5-6 to 11.<br>» Batch sizes and WIP were cut in half.<br>» Raw materials, WIP and finished goods dropped 40% in the first 18 months.<br>» Due date performance improved.<br>» OPT as a simulation tool was of particular benefit. |
| <u>CASE 10</u> (Jones and Roberts 1990)<br>1- Caron Yarn Company (US)<br>2- Supplier to the sweater, cap, glove and yarn kit industry.<br>3- ? | » Existing planning and scheduling methods were resulting in excessive inventory, without improving the customer service.<br>» Production runs were planned around the largest batch possible to minimise setups. This resulted in not needed batches to fill demand and obsolescence.<br>» The inaccuracy of manufacturing reports was another problem. | » It took a year to implement OPT.<br>» Updated data was available twice a week - after OPT implementation- opposed to the previous once a month schedule revisions.<br>» They had to accept the change in the old style scheduling methods and without the widespread support from management "..it is not possible to obtain significant improvement". | » After a year: 94% of the orders were completed and inventory was reduced by $1 million.<br>» After 2 years they completed 96% of the orders and reduced inventory in $1.2 million.<br>» Warehousing space was freed up.<br>» With the new reporting system improvements have been seen in communication and planning. There is more visibility to prioritise.<br>» Greater customer satisfaction.<br>» Quality is impacted: with lower inventory, problems can be better spotted and corrected. |

| | | | |
|---|---|---|---|
| CASE 11 (Jones and Roberts 1990)<br>1- STC Components Semiconductor Division (Sidcup/Kent)<br>2- Integrated circuits.<br>3- High volume low margin devices, with small machines of limited capabilities being used in manufacturing.<br>(T plant) | » There was no data base system to provide reports on WIP.<br>» Now, STC produces highly complex devices with many mixed technologies, and the manufacturing process is controlled by the in-house generated marketing demands.<br>» A major current scheduling problem include producing quantities of parts that do not sell. | » OPT was bought, but initially it was not fully implemented as a result of the rapid growth and change in technologies, product focus equipment and management re-structuring.<br>» To re-implement OPT, STC has had to create a realistic model of their very complex manufacturing process (this was one of the challenges due to the nature of their ever changing industry). In addition, they had to alternate planning for the case of machine breakdowns. | » They hope OPT will help them reduce WIP and improve due-date performance. |

* Unsuccessful OPT implementations

Not all OPT implementations have finished in success. However, there is a lack of published papers revealing the reasons for the failure. The few cases of unsuccessful OPT installations obtained from personal contact or published articles are:

» In the early days of OPT (around 1978), when creating the schedule took as much as 48 hours of computer time, Black & Decker got so impatient that it dropped the system (Bylinsky 1983).

» In those early days as well, Deere & Co. found that its own production control program suited better than OPT (Bylinsky 1983).

» In a private communication with Mike Rose (scheduler of British Alcan, North Wales), he declared that they attempted to install OPT in their company, but they found the software (a) difficult to interface with their production control systems, and (b) that it lacked the interactive capabilities provided by other scheduling packages. However, the main reason why OPT was not implemented in British Alcan was because it could not adequately represent a special production situation:

- Most of the production demands loaded in OPT showed that the CCR of the system was placed almost at the end of the production process. Therefore, the software always created the optimum schedule for the constraint, and subordinated the whole plant to it. However, previous to the constraint it was a heat treatment operation where the products were grouped according to shapes and sizes in order to optimize furnace's capacity. This particular product sequence in the heat treatment influenced greatly the optimum schedule of the constraint, and OPT was not capable of representing it.

» Gordon Brown, manager of Avesta Sheffield Group, exposed the reasons why OPT was not successfully installed in his company (The Institute of Materials Seminar, Production Scheduling in Metals Industry -1994-):

- Company background: Avesta Sheffield Group is a supplier of Stainless Steel formed by the merger in 1992 of Avesta AB of Sweden and British Steel Stainless. They are the largest supplier of Stainless Steel Plate (European Market Share of 33%), with the Sheffield Plate Mill representing the 30% of the division's output. Delivery reliability and short production lead time are the two major order winning criteria. Furthermore, (a) all production is to customer order, (b) they have 90% jobbing orders, and (c) there are large number of finished goods variants.

In 1990, delivery reliability was 25%, production lead time was 8 weeks, and the number of stock turns was 3.

- Proposed changes: Avesta decided, after a Business Analysis, to invest in the training of white & blue collar personnel and the implementation of a software system (OPT). OPT implementation was justified based on the following two arguments: (1) to handle the detail for scheduling in a realistic timescale, and (2) to serve as a pilot trial for the rest of the works (Coil).

- Results obtained: OPT software development was frozen in 1993 due to:

1) The implementation of OPT software was unable to match the pace of change resulting from the merger.

2) OPT was, with difficulty, able to match the technical scheduling challenges made by the hot rolling and in-line heat treatment of different stainless steels.

3) OPT development was unable to keep pace with the dynamic changes in the constraints.

On the other hand personnel training on material flow and bottleneck throughput brought the following benefits: increased delivery reliability from 25% to 80%, reduced production lead time from 8 weeks to 2.5 weeks, and increased number of stock turns from 3 to 11.

- Final conclusions: as a result of the failed OPT implementation, they conclude that the scheduling package in a Jobbing Plate Mill has to be: flexible, must assist the human scheduler, and the scheduler must be able to tailor the final schedule.

## APPENDIX D: ASSESSING DISASTER UNDER DIFFERENT PRODUCTION SITUATIONS

*** Assessment aspects**

DISASTER's assessment aspects can be divided in two main groups:

1- Operational features: initially, DISASTER's capability of realistically represent the peculiarities of different production environments will be examined. Then, once DISASTER is being runned, the usefulness of the operational features it provides (i.e. overtime, setup savings, offloading, batch splitting, and rescheduling) will be analyzed on the perspective of the support they give in the many situations the user can encounter.

2- Schedule evaluation: the schedules produced by DISASTER will be evaluated according to their:

(a) *Feasibility*: the schedule should be possible to follow once it is released to the shop floor (all conflicts between constraints should be removed so that it does not contain any logical contradictions).

(b) *Objectives achievement*: the schedules are judged according to the achievement of TOC's Goal: (I) achieve the maximum throughput, (II) inventory should be maintained to a minimum and only in order to guarantee throughput, and (III) operating expense -in terms of overtime- should only be used to protect throughput.

(C) *Immunization against production disturbances*: the schedule should handle production disturbances by protecting itself against their effect. According to Goldratt (1990b), if any perturbation will necessitate rescheduling, that would be the best indication that it has not been properly immunized.

*** Production situations assessed**

Different production situations will be modelled in DISASTER and the validity of it's schedules assessed with the aid of a simulation package. The production situations studied in DISASTER will be divided into:

1 - General production circumstances

2 - Shop floor common situations

3 - Special production cases

* **General production circumstances**

The infinite number of different production situations that can be encountered in real manufacturing environments make impossible the task of assessing all of them. However, there are some features from which a general framework can be built, so that specific production circumstances can be located in that framework. The features that define this general structure are:

■ Overall system capacity: whether the resources of the system have enough capacity to answer the demand or not.

■ Complexity of the system: system complexity is determined by, for example, the number of resources, number of stations (operations), number of final products and raw materials, production route (convergent points, divergent points, line), and many other particular factors (e.g. key resource from which most of the products have to pass, a resource with long set ups, a resource with many breakdowns, assembly of many common parts, etc..)

■ Severity of the constraint: the constraint is considered severe when it's load/capacity ratio is much higher than the rest of the resources. If most of the resources have similar ratio, the system is said to be close to balance.

■ Demand stability: if the demand pattern does not change very often, final products' demand is considered stable.

Furthermore, there are many other factors not included in the above list that can directly affect the scheduling course, and thus, the final result. Some of this factors are: the timing and quantity of the production orders, the selected parameters (especially the scheduling horizon and the buffers), the initial input data (particularly the number of final products, stations and raw material, and the set up and process times), the peculiarities of the modelled system (existence and location of key machines, number of CCRs or bottlenecks, machines with long setups or many breakdowns, etc..), and the course followed by the user.

The infinite possible combinations that can be created make impossible to assess all of them. Therefore, general production circumstances are extracted by linking some of the above features with the aim of evaluating DISASTER under a situation that most generally represents diverse production environments. Moreover, not all the assessment aspects will be analyzed in all the cases; only those that would reflect in the best way the manufacturing circumstance will be studied in each case.

**CASE - 1 > A system with overall excess capacity and a well defined CCR**

Fairly complex system with overall excess capacity and a specific production demand that originates a severe constraint (that is not a bottleneck).

(A) Model description

The model utilized contains two final products, five different raw materials, six resources, and 14 operations (stations) (see Figure next page). It must be noticed that there is a WIP of 20 pieces between stations A1 and A3.

Final products demand contains one order of 60 units for each final product. They both have the same due date (18/3/94).

DISASTER's parameters are defined in the following way:

» Scheduling horizon: start> 14/3 ------ end> 18/3 (5 working days - 8 hours per day)

» Buffers length: shipping> 4h, constraint> 4h, assembly> 4h.

» Overtime allowed: daily>2h., weekly>10h., weekends> 0h.

» Protective capacity: 5%

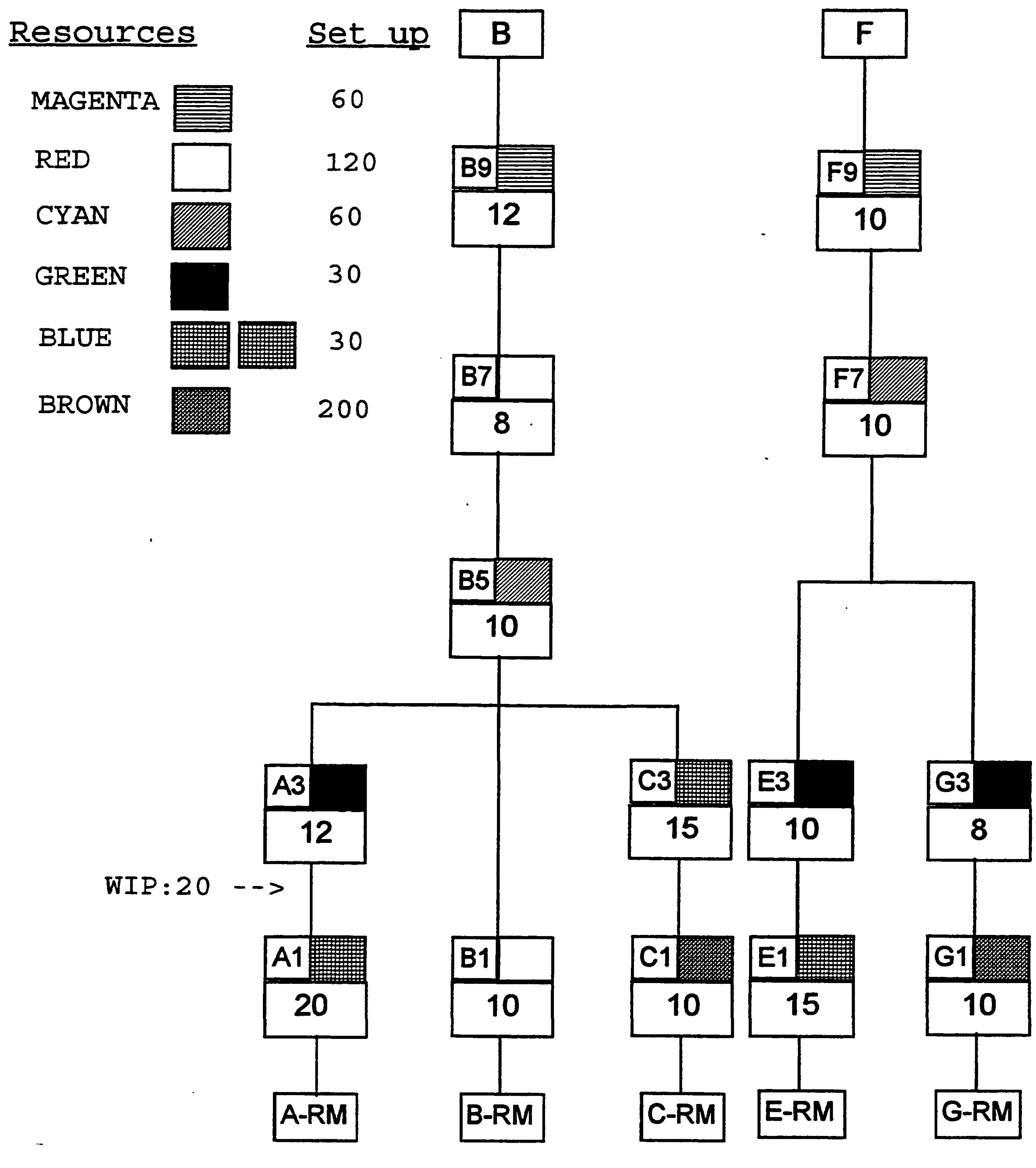
(B) Scheduling process and final results

■ Identification: the GREEN resource is loaded at 75% of its available capacity; while the next one on the list is MAGENTA with 55%. Therefore, the user selects resource GREEN as the first constraint of the system.

■ Ruins: The ideal schedule DISASTER produces for the GREEN resource is:

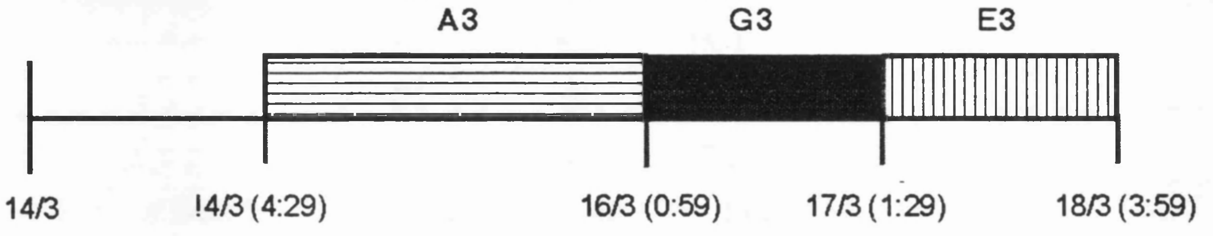
| | Start | End |
|---|---|---|
| A3 | 16/3 at 7:29 | 18/3 at 3:59 |
| E3 | 17/3 at 1:29 | 18/3 at 3:59 |
| G3 | 17/3 at 3:29 | 18/3 at 3:59 |

As can be noted, the shipping buffer is subtracted from the orders due dates and the batches are scheduled backward assuming finite resource capacity but infinite number of available resources (batches are put on top of each other).



Resources
Set up
MAGENTA
60
RED
120
CYAN
60
GREEN
30
BLUE
30
BROWN
200
B
F
B9
12
F9
10
B7
8
F7
10
B5
10
A3
12
C3
15
E3
10
G3
8
WIP:20 -->
A1
20
B1
10
C1
10
E1
15
G1
10
A-RM
B-RM
C-RM
E-RM
G-RM

■ Drum: the batches are sequenced in the following way:




DISASTER does not follow any particular logic to arrange the blocks. The three blocks have the same ideal end date (18/3 at 3:59) and they are ordered backward assuming the finite capacity of the resource. As the GREEN resource is a CCR (75% load), no conflicts arise in the Drum and the inherent idle time is located at the beginning of the period (DISASTER seeks to meet the due dates as the main factor to prioritize the jobs).

■ Subordination: in the subordination process, a First Day Load situation occur with the BROWN resource (station G1). This station contains a peak of 1:52 h. that must be solved. At this point of the scheduling process two different decisions can be taken:

» Decision 1 > allocate overtime. DISASTER automatically allocates 2 hours of overtime for station G1 for the beginning of the scheduling horizon.

» Decision 2 > Identify resource BROWN as the second constraint and create its Drum. The Drum DISASTER creates for this second constraint is:

| | Start | End |
|---|---|---|
| G1 | 15/3 at 2:01 | 16/3 at 7:21 |
| C1 | 16/3 at 7:21 | 18/3 at 4:41 |

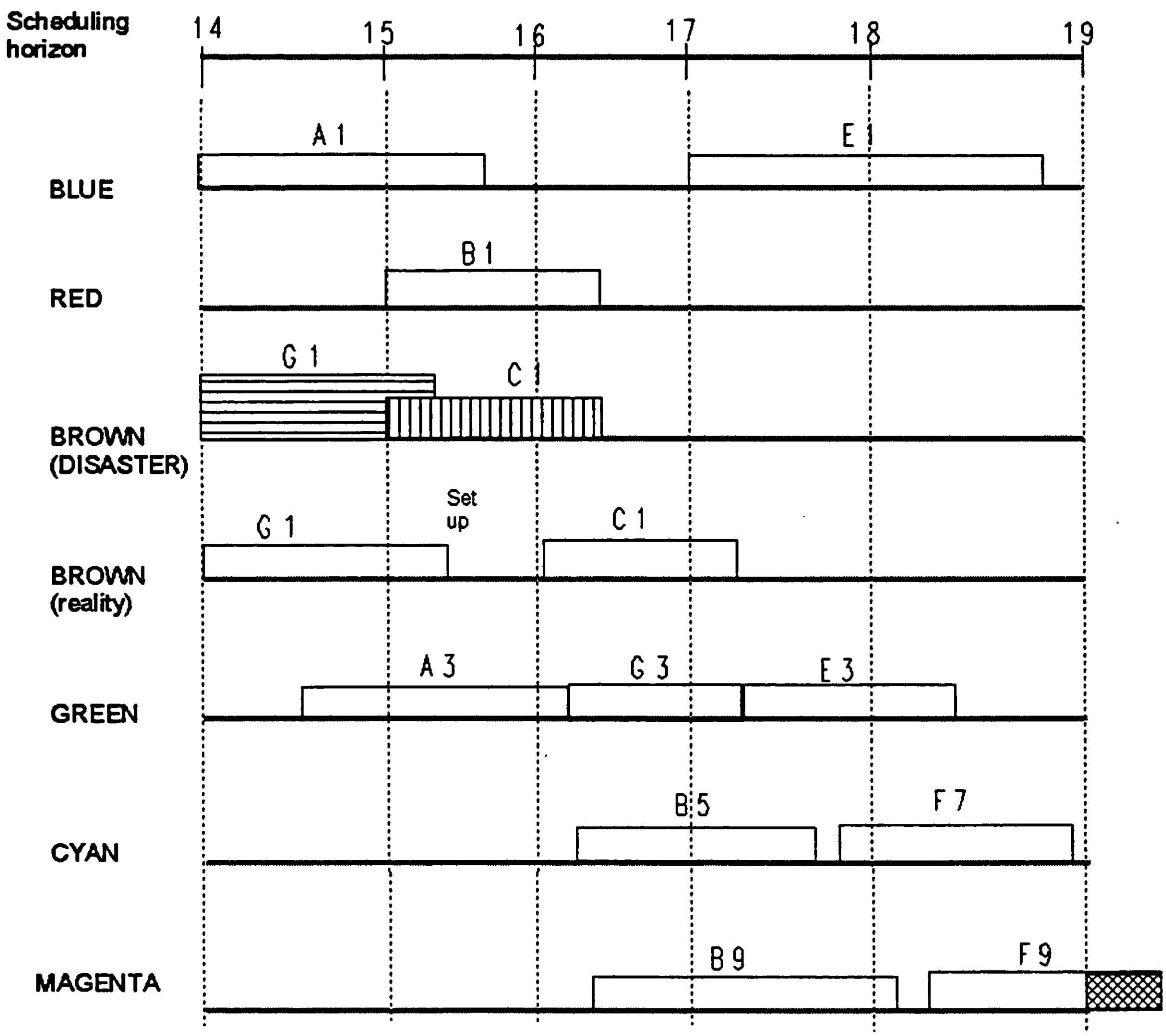
Subordinating the rest of the system according to this second Drum, "Red Lane Peak" cases arouse for B9 and B5 stations. It was decided to allocate overtime to solve these conflicts.

■ Final results. The material release dates for the two decisions are:

| | Station | Quantity | Date |
|---|---|---|---|
| » Decision 1 > | A1 | 40 | 14/3 |
| | G1 | 60 | 14/3 |
| | B1 | 60 | 15/3 |
| | C1 | 60 | 15/3 |
| | E1 | 60 | 17/3 |
| » Decision 2 > | A1 | 40 | 14/3 |
| | B1 | 60 | 15/3 |
| | E1 | 60 | 16/3 |

(C) Schedules feasibility

Looking at the Drum and the material release dates, it can be calculated whether the schedules produced for the two cases can be met in the shop floor or not.



» Decision 1 > Initially, checking the Drum in isolation, it must be considered realistic only assuming (a) that batch overlapping is allowed and (b) the upstream and downstream resources will be dedicated to feed the constraint and process the parts coming from it. Looking at it in more detail, if transfer and process batches would be considered equal, there would not be enough time, for example, to feed A3 the 14/3 at 4:29 because processing 40 pieces at A1 would take about 14 hours and this resource is scheduled to start the 14/3. The same case would happen with the products released by E3 the 18/3 at 3:59 (they would only have 4 hours to be processed in stations B5, B7 and B9. Something totally impossible without overlapping).

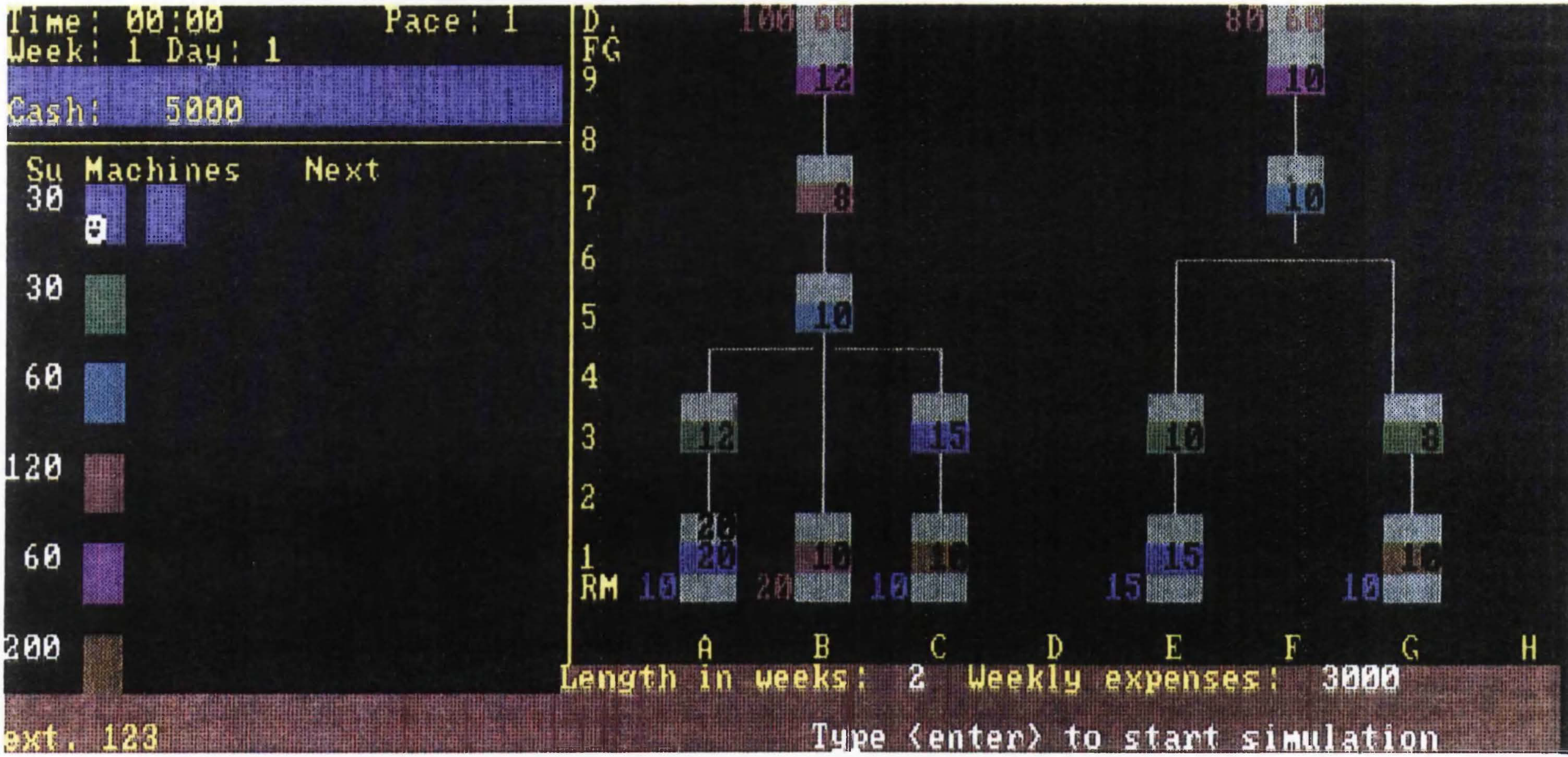
Looking at both, the Drum and the releasing days, it can be seen that by the time A3 has finished processing the parts, these will be blocked in front of assembly B5 waiting for parts coming from B1 and C3 -fed by C1- (B and C parts are released to the plant the 15/3, and assuming they can be processed as soon as they arrive -something impossible for C1 because this resource will be busy at G1- assembly would still be idle for some time).

The same case was modelled using a simulation package used by the Avraham Goldratt Institute -AGI- to demonstrate the TOC principles (see Figure next page). As it was already guessed, following the suggested release dates, the operations fed by the constraint (specially both assemblies B5 and F7) stayed idle for the first half of the scheduling period, and by the time they could start processing some parts, it was not enough time to meet demand. Therefore, the schedules produced by DISASTER cannot be considered realistic.

» Decision 2 > the same overlapping and lack of coherence between the Drum and the material release dates can also be seen in this case. For example, the final part released from C1 the 18/3 at 4:41 would only be shipped, if the transfer batch for all the succeeding resources is one, and of course, if these resources are not busy processing other parts (something that happens if we follow the proposed schedules).

(D) Objectives achievement

As long as the schedules produced by DISASTER are not feasible, the aimed objectives would not be achieved. Even having enough overall excess capacity in the system, the schedules produced would not be able to meet the demand (and thus,


Time: 00:00
Pace: 1
Week: 1 Day: 1
Cash: 5000
Su Machines Next
30
30
60
120
60
200
D.
FG
9
8
7
6
5
4
3
2
1
RM
A B C D E F G H
Length in weeks: 2 Weekly expenses: 3000
ext. 123
Type <enter> to start simulation

throughput will be lost). The following results were obtained from the simulations performed of the above two cases:

» Decision 1> All 'B' and 31 'F' final products sold at the end of the scheduling period.

» Decision 2> All 'F' and 0 'B' final products sold.

Looking at all the model in general and assuming variable process batches (something ignored by DISASTER -it equals order's quantity with the process batch-) the following schedule can be manually created:

| | Station | Date | Quantity |
|---|---|---|---|
| Drum -----------> | A3 | 14/3 at 0:00 | 20 |
| | E3 | 14/3 at 5:00 | 60 |
| | G3 | 15/3 at 6:00 | 60 |
| | A3 | 16/3 at 5:00 | 40 |
| Material release | B1 | 14/3 at 0:00 | 20 |
| | C1 | 14/3 at 0:00 | 20 |
| | E1 | 14/3 at 0:00 | 60 |
| | G1 | 15/3 at 2:00 | 60 |
| | A1 | 16/3 at 4:00 | 20 |
| | B1 | 16/3 at 4:00 | 20 |
| | C1 | 16/3 at 4:00 | 20 |

Running the simulation according to this schedule, all the products were shipped on time and still 3 hours remained. Even without splitting the process batches, releasing A1, B1 and C1 at the begining of the scheduling horizon, demand could be met. However, DISASTER was not able to achieve the objectives due to the creation of infeasible schedules that did not take into account the peculiarities of the system as a whole (it was not consistency between the Drum and the Rope). The main reason for this lack of coherence it seems to be the key role the correct buffer setting has in the final results (nevertheless, several different buffer sizes were checked -e.g. 1h., 2h., 3h., 5h, 6h., 7h., 8h., 10h.- and still the schedules produced were not the optimum ones).

(E) Immunization against disturbances

Once the schedules produced by DISASTER are analyzed, the choice of the buffer size that would lower production disturbances' effects appears essential. It has to be taken into account that all delays caused by production disturbances would lead to a throughput loss specially at the end of the scheduling period when assemblies are able to process the parts coming from the constraints.

**CASE - 2 > A system with lack of capacity and a well defined bottleneck**

A complex system with lack of overall capacity (there are several bottlenecks in the system) and a specific production demand that creates a severe bottleneck.

(A) Model description

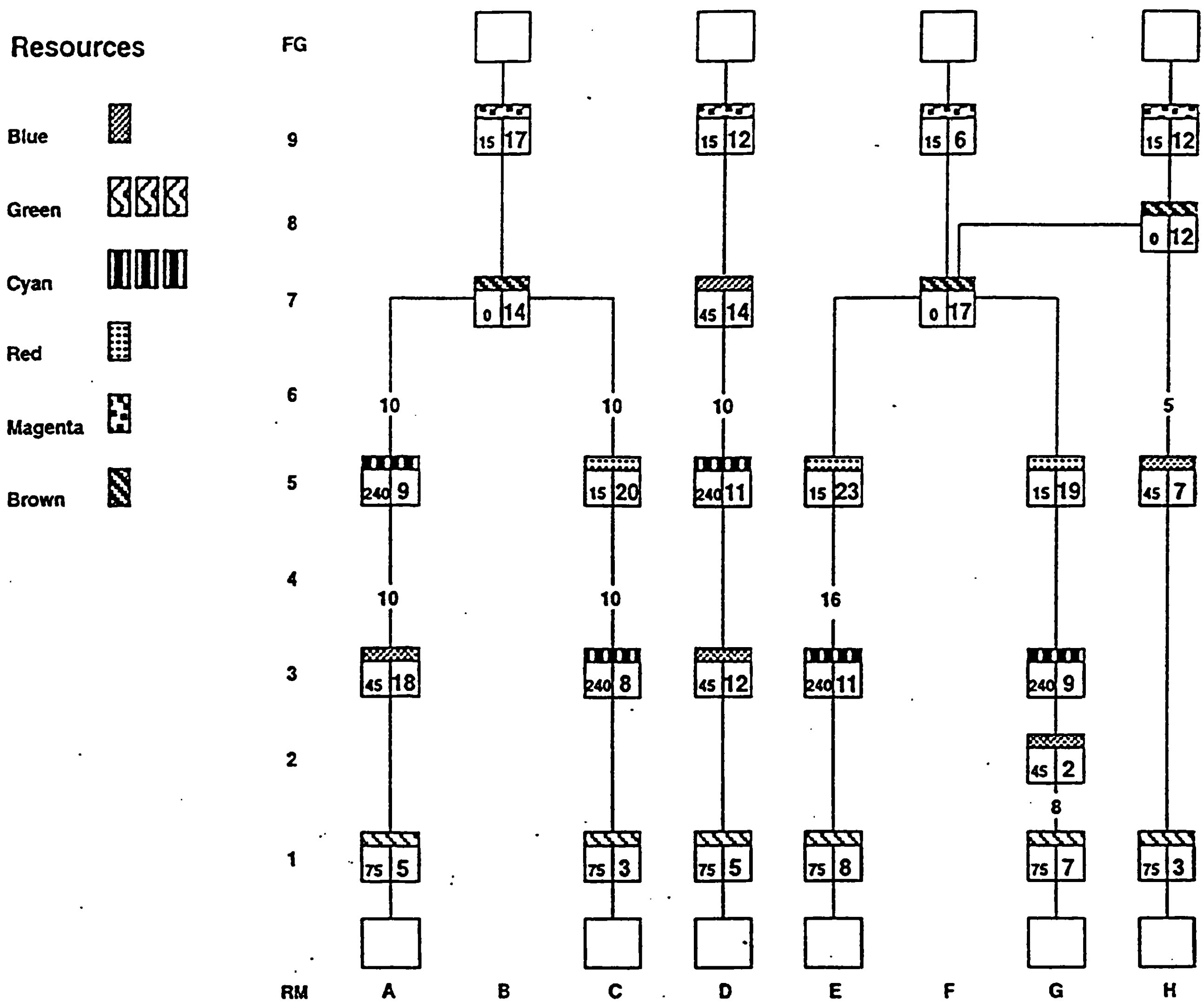
The model selected for this case is one of the demonstration examples provided with the DISASTER package (NET141). However, some slight changes have been made to accommodate it to the characteristics of the case. The production system contains 4 final products, 6 different raw materials, 6 resources, 26 stations, and 13 different orders (see Figure next page). 4 more orders have been included to saturate resources' available capacity.

In this case, more attention will be paid to the operational features provided by DISASTER during the scheduling process, than to the feasibility of the schedules produced (in contrast to Case-1).

(B) Scheduling process

■ Identification: the loads of the resources are: RED - 169%, MAGENTA - 113%, BROWN - 105%, BLUE - 86%. The other two resources are not so fully loaded. As a result, there are three bottlenecks in the system, but one of them (resource RED) is more severe than the others. Resource RED is identified as the first constraint of the system.

■ Ruins: the ideal schedule is created subtracting the shipping buffer from the orders due dates.



Resources
Blue
Green
Cyan
Red
Magenta
Brown
FG
9
8
7
6
5
4
3
2
1
RM
A
B
C
D
E
F
G
H
15 17
15 12
15 6
15 12
0 12
0 14
45 14
0 17
10
10
10
5
240 9
15 20
240 11
15 23
15 19
45 7
10
10
16
45 18
240 8
45 12
240 11
240 9
45 2
8
75 5
75 3
75 5
75 8
75 7
75 3

■ Drum: the lack of capacity of the constraint, makes some batches be scheduled later than their ideal date. The following blocks are coloured in red:

| Station | Order (due date) | Time late |
|---|---|---|
| G5 | H - 7/8 | 10 min. |
| G5 | H - 13/8 | 7:06 h. |
| E5 | H - 13/8 | 18:51 h. |
| G5 | F - 14/8 | 20:36 h. |
| E5 | F - 14/8 | 32:21 h. |

Adding all the time the orders are late, there are around 78 hours for which the constraint lacks capacity. The user faces now the situation whether delay some orders and warn the customer of that delay, or try to obtain the missing 78 hours by creating a schedule for the constraint. In hour case, the second option is followed to check the support DISASTER provides in solving the conflicts.

■ The following actions are undertaken to remove the conflicts from the Drum:

(a) Automatic set up saving option > no batches can be "glued" without breaking one of the three rules (see section 10.3.3.3).

(b) Introduce 100 set up ratio > two hours are saved. However, changing the blocks from their initial position two more orders are added to the late orders list. This option is not employed.

(c) Automatic overtime> DISASTER takes into account the daily overtime determined in the initial parameters to allocate overtime. As a result of applying this option, only three orders still remain late, but with about 30 hours required:

| Station | Order (due date) | Time late |
|---|---|---|
| E5 | H - 13/8 | 6:51 h. |
| G5 | F - 14/8 | 6:36 h. |
| E5 | F - 14/8 | 18:21 h. |

(d) Offload the parts to be performed in station E5 (order H - 13/8) to the less loaded resource of the system (CYAN). Of course, it is assumed that it can be done. As a consequence of the space left by this batch, the succeeding ones are moved backward and only one order is still late: E5 (F - 14/8), 6:21 h. late.

The user at this point decides that no more work can be offloaded and that enough overtime has been employed at the constraint. A late delivery for this order is accepted.

■ Subordination: the first conflict that arises at the subordination stage is a "Red Lane Peak" for resource MAGENTA (station B9). The peak size is 3:12 hours. The conflict is solved by allocating 4 hours of overtime.

The next conflicts to be solved are three "First Day Load" cases:

| Resource | Peak size | % Buffer eaten |
|---|---|---|
| CYAN | 2:50 | 0.35 |
| MAGENTA | 4:01 | 0.5 |
| BLUE | 18:35 | 2.32 |

The first two cases are ignored, supposing that in the worst of the situations still half of the buffer is left to protect the system against disturbances (MAGENTA).

In resource BLUE two decisions can be taken: (I) allocate overtime (and the subordination process would finish), or (II) try to reduce the 18 h. peak by scheduling its batches. The second option is followed and a second constraint is defined.

In the new Drum, three of the batches are late with an overall delay of 35 hours. The solutions taken to remove the conflicts are:

(a) Automatic set up saving > 135 min. are saved.

(b) Allocate the allowed overtime > the three orders still continue late, but with only 7:30 hours of delay.

(c) The batch with the higher load is offloaded to resource CYAN, and the remaining two orders are ignored.

In the subordination process, three "Red Lane Peak" cases take place:

| Resource | Peak | Resolution |
|---|---|---|
| MAGENTA (H9) | 39 min. | Ignore |
| BROWN | 9 h. | Overtime |
| MAGENTA (D9) | 2 h. | Overtime |

No more conflicts arise and the output files can be finally generated. The Drum output file contains 31 scheduled operations for the two identified constraints; while the material release file contains 20 scheduled actions.

(C) Operational features

The options provided by DISASTER to remove the scheduling conflicts play an important role in this case. Other scheduling packages do not allow the user select the actions to be taken to solve the problems, and they simply produce a schedule from the introduced inputs. The interactive capability and the decision responsibility put in the hands of the user are fully exploited in this case. However, the following comments can be drawn related to some of DISASTER's operational features:

» Fast options application: before revising the options, it must be mentioned that each decision the user takes is instantly performed. So, the user can rapidly see on the screen the outcome of the decision taken.

» Set up ratio option: this option did not bring any set up time reductions in this particular case. Moreover, both times it was used it complicated the schedule instead of bringing any benefit. However, in other situations it could be useful.

» Undo option: this option is particularly helpful in the cases where the user has taken the wrong decision and wants to correct the mistake (like in the above option).

» Automatic overtime allocation: is very practical as long as the user is sure that the overtime hours defined in the parameters are correct. Further particular overtime allocations can be done in the batch analysis stage.

» Offload option: this option, like the last one, should only be used when the user is positive that it can be employed. Otherwise, might solve conflicts in the Drum on the behalf of generating them in other non-constraint resources.

» Project data modifications: project data can be changed at any stage of the scheduling process. However, *each change make the process start again* (very frustrating when the user has spent a long time solving the conflicts and faces the situation where in order to solve one problem, data must be changed and the scheduling process restarted -and maybe then, the circumstances may be different and different decisions should be taken-).

» Manual reschedule: this option gives the opportunity to manually change the location of the blocks. Although in our case it brought more disadvantages than benefits (in terms of increased delays), is should be considered very practical when employed by experienced schedulers (e.g. the case of dependent set ups or when normal shop floor practices are not contemplated by the software).

» Batch splitting: beneficial when the customer requires periodical product releases (it would avoid creating single small orders). However, the schedule of the splitted batches will be responsibility of the user -by using the above option- and in the case of a bottleneck resource it will increase the time employed in set up.

» New constraint identification: at the "Red Lane Peak" and "First Day Load" situations the user can identify a new constraint and create a new Drum. Time can be saved by creating new schedules. However, there is the risk of generating more conflicts with previous Drums, and increase dramatically the time spent in the scheduling process (this is an important aspect to take into account while scheduling, for example, the current case or even more complex ones).

» Output files: related to the Drum file, the user -from our point of view- can get confused looking at the data provided (there are lots of numbers without any heading)(see Figure below). On the other hand, the information included in the raw material and overtime files should be considered very helpful (they contain the raw material net requirements and dates, and the overtime date, location and size).

```
  3              RED                          G5              H-FG/900807       12  1
00  15 900806  7:59 900806  8:06 900807  2:09  1 TPP  0
  4              RED                          G5              F-FG/900808       10  1
00  15 900807  7:59 900807  2:09 900807  5:19  1 TPP  0
  5              RED                          E5              F-FG/900808       10  2
00  15 900807  7:59 900807  5:19 900807  9:24  1 TPP  0
  6              RED                          C5              B-FG/900809       16  2
00  15 900808  7:59 900807  9:24 900808  4:59  1 TPP  0
  7              RED                          G5              H-FG/900810        8  1
00  15 900809  7:59 900808  4:59 900808  7:46  1 TPP  0
  8              RED                          E5              H-FG/900810        8  2
00  15 900809  7:59 900808  7:46 900809  1:05  1 TPP  0
  9              RED                          C5              B-FG/900813       30  2
00  15 900810  7:59 900809  1:05 900810  1:20  1 TPP  0
 10              RED                          G5              H-FG/900813       30  1
00  15 900810  7:59 900810  1:20 900813  1:05  1 TPP  0
 11              RED                          G5              F-FG/900814       30  1
00  15 900813  7:59 900813  1:05 900814  0:35  1 TPP  0
 12              RED                          E5              H-FG/900813       30  2
00  15 900810  7:59 OFFLOADED to resource CYAN
 13              RED                          E5              F-FG/900814       30  2
```

(D) Schedules feasibility

Two of the Drum orders are checked in order to determine whether they are in consonance with the Rope. The first one is an order of 8 units for H to be shipped the 10/8. The constraint G5 is scheduled to start the 8/8 at 4:59 and finish at 7:46. The constraint E5 starts when G5 finishes and it ends the 9/8 at 1:05. E1 material is released the 7/8 (so it has 13 hours to reach the constraint. This can be considered realistic). G1, on the other hand, is not scheduled because there are 8 units of WIP between G1 and G2. Shop floor operators will process the parts when they arrive, thus, this 8 units will be processed the first day of the scheduling period (6/8) and will be waiting in front of G5 till the 8/8 at 4:59 (the constraint will be protected by stocking inventory for more than two days -too much protection-).

The second order analyzed was the one the user decided to leave without solving: 30 F products for the 14/8. Constraint G5 is scheduled to start the 13/8 at 1:05 and finish the 14/8 at 0:35. E5 will start when G5 finishes, and end the 15/8 at 2:20. Material for G5 is released the 8/8 (with enough time to reach the constraint). However, E1 is scheduled to start the 13/8, with only 8 hours to process the 30 parts at resources E1 and E3 (still enough time but assuming batches are overlapped and that the upstream resources are not busy with other parts)

(E) Immunization against disturbances

In Case 1 buffers were considered too small to handle production disturbances. Case 2 is far more complex, therefore, only when the constraint is identified the user will be able to determine the size of the buffers. Additionally, buffer sizes can only be accurately defined after the schedules are created. At this point, if buffer modifications are decided, the scheduling process would have to start again (making the user feel that a long time is required until an acceptable schedule is finally found).

**CASE - 3 > A system with overall excess capacity and close to balance**

Simple system with overall excess capacity and a single product demand that equally loads system's capacity (close to balance situation).

(A) Model description

The model employed for this case is a simple production line. The line produces a single product (A) and contains 6 stations (each of them utilizes a different resource).

| Resources => | BLUE | GREEN | CYAN | RED | MAGENTA | BROWN |
|---|---|---|---|---|---|---|
| | 13 | 14.5 | 14 | 15 | 13 | 14 |
| Set up => | 20 | 25 | 30 | 30 | 40 | 35 |

Production demand is formed by three orders containing the following quantities and due dates: (1) 40 products for the 8/6, (2) 50 products for the 9/6, and (3) 30 products for the 10/6.

The initial parameters are set as follows:

» Scheduling horizon: start> 6/6 -------- end> 10/6 (5 working days, 8h. per day)

» Buffers length: shipping>4h., assembly>4h., and constraint>6h.

» Overtime: daily>2h., weekly>10h., and weekends>0h.

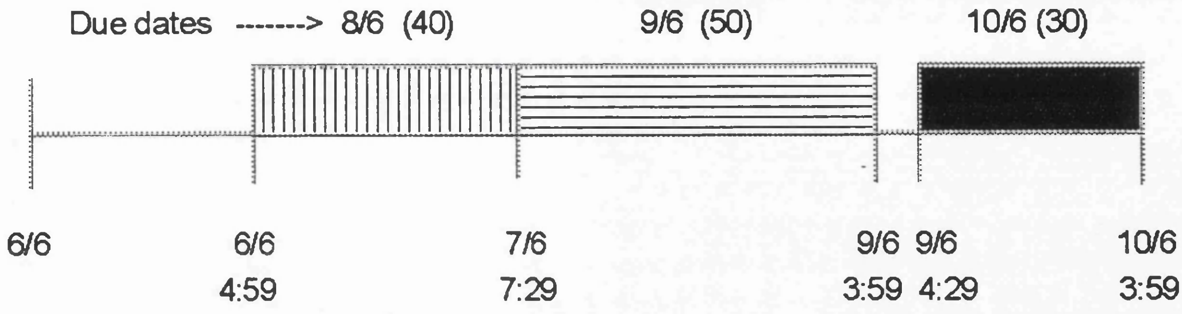
» Protective capacity: 5%.

(B) Scheduling process and final results

■ Identification: from the above data, the load/capacity list is formed by: RED>75%, GREEN>72.5%, CYAN>70%, BROWN>70%, MAGENTA>65%, and BLUE>65%. The system contains overall excess capacity and the production loads are similarly distributed.

■ Ruins: the shipping buffer is subtracted from the final orders due dates to create the ideal schedule.

■ Drum:




DISASTER's rule to prioritize the batches is based on the orders' due date. As the constraint of this case has enough capacity to answer demand, the Drum contains two gaps: the first one of 5h. at the beginning of the scheduling horizon, and the second one of only 30 min. between the completion of the order of 50 products and the beginning of the order of 30 products.

Before subordinating the rest of the system to the Drum, it can be seen that conflicts will arise with the processing dates of the resources preceding the constraint (the constraint buffer is 6h., and there are only 5h. from the beginning of the scheduling horizon until the first part is scheduled at the constraint).

■ Subordination: as it was already guessed, three "First Day Load" situations appear:

| Resource | Peak size | % of Buffer eaten |
|---|---|---|
| GREEN | 4:02 | 0.67 |
| CYAN | 3:18 | 0.55 |
| BLUE | 1:38 | 0.27 |

The user removes the conflicts by: (a) ignoring the BLUE resource case (73% of the constraint buffer is still left to protect the constraint against disturbances), (b) allocating overtime for resource CYAN at the first day of the scheduling period, and (c) defining resource GREEN as the new constraint.

The Ruins and the Drum are generated. As there are no contradictions between the two Drums, the user decides not to take any action. In the subordination process the same "First Day Load" for resource BLUE appear and is again ignored. No further conflicts take place and the output files are generated.

■ Final results: raw material is scheduled to be released to the line for the 6/6 (90 products) and for the 8/6 (30 products).

(C) Operational features

When the user decided to allocate overtime in resource CYAN to solve the "First Day Load" problem, two options could be employed: (1) allocate only the time required to solve the peak (3 hours in our case), or (2) allocate overtime for the whole batch (14 hours). In this case the first option was implemented, and thus, DISASTER automatically allocated 4 hours. The user is not given the possibility to decide the time to employ to solve the peak (maybe allocating only one hour is enough because more than half of the buffer is still left). Furthermore, DISASTER overlooks the overtime defined at the initial parameters, and employs all the time required to solve the peak.

(D) Schedules feasibility

Analysing the Drums and release dates, unrealistic situations does not take place in this model. As in previous cases, batch overlapping is taken for granted. However, in this case, the existence of a single product eliminates the possibility of schedule irregularities between resources (they will be either processing product A or idle).

To guarantee that no conflicts arise in the production process, the same current situation was simulated. As a result, it could be observed that the schedules were feasible and due dates could be met without any further problems.

(E) Objectives achievement

The established objectives are not achieved by only meeting orders' due dates (by ensuring throughput). Throughput should be maximized, but inventory and operating expenses should also be simultaneously minimized. When the model was simulated without taking into account process times fluctuations and machine breakdowns, the parts -due to the size of the buffers- had to wait in front of the constraint at the beginning of the scheduling period (the start was scheduled at 4:59). Similarly, at the end of the period, they reached shipping 4:20 hours ahead on time. This obviously leads to an increase in WIP and final products inventory (is the price paid for the protection against

Murphy). Furthermore, the parts reached the constraint without having to utilize the 4 hours of overtime for resource CYAN allocated by DISASTER's suggestion (operating expenses would have unnecessarily increased).

The line was also simulated having all the resources activated for the whole scheduling horizon. The final result was (even taking Murphy into account in this case) that the line, working continuously, would have been able to produce 32 products more than the 120 scheduled. Obviously, as demand was only for 120, the extra 32 would have stayed as final goods inventory (moving the system against the Goal). This demonstrates that the constraint of this case was the market.

(F) Immunization against disturbances

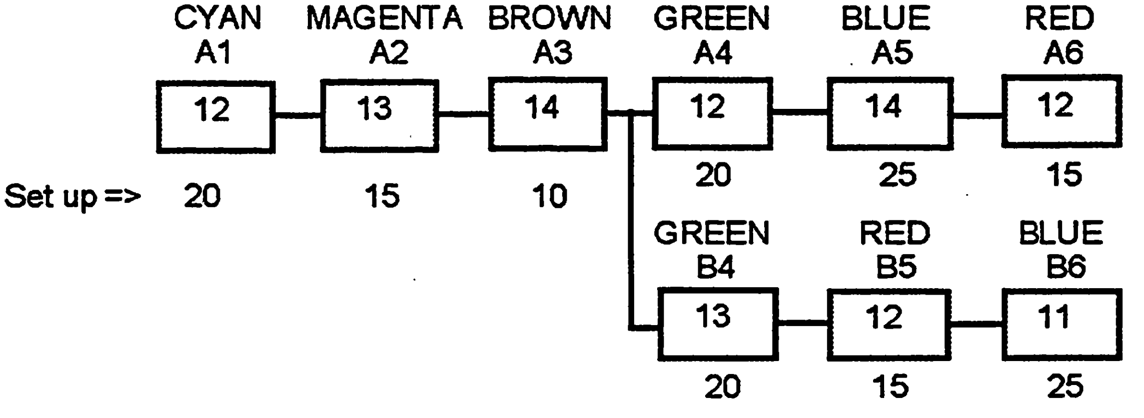
Taking into account production disturbances, the simulation showed that the parts - as in the above case- at the beginning accumulated in front of the constraint, and at the end reached shipping with still 3:45 hours left. Thus, -in our simulation- only 15 min. from the 4 hours of shipping buffer defined were eaten by the effect of Murphy (buffer sizes were set too high to protect the system).

## CASE - 4 > A system with lack of capacity and close to balance

Fairly simple system with overall lack of capacity due to the demand placed on it and a close to balance situation (several bottleneck resources of similar size).

### (A) Model description

The model used for this case is formed by a production line with a divergent point in the middle of the process. Two different products are produced (A and B) in the 6 resources -9 stations- that form the system.




The demand for the two final products is as follows:

| Product | Due date | Quantity |
|---|---|---|
| A | 7/6 | 20 |
| A | 8/6 | 25 |
| A | 9/6 | 30 |
| A | 10/6 | 30 |
| B | 7/6 | 15 |
| B | 8/6 | 20 |
| B | 9/6 | 30 |
| B | 10/6 | 40 |

The parameters are:

» Scheduling horizon: start>6/6 ----- end>10/6

» Buffers length: 4 h. the three of them.

» Overtime: daily>2h., weekly>10h., and weekends>0h.

» Protective capacity: 5%.

(B) Scheduling process and final results

■ Identification: the demand placed on the resources saturates all of them above their available capacity: BROWN>122.5%, MAGENTA>113.75%, BLUE>109.38%, GREEN>109.38%, CYAN>105%, and RED>105%. The outcome is the existence of 6 bottlenecks and resource BROWN as the CCR of the system. This resource is thus identified as the first constraint.

■ Ruins: DISASTER shows that in the ideal location of the batches (i.e. assuming unlimited number of resources), sometimes three equal resources processing at the same time would be required.

■ Drum: as resource BROWN is a bottleneck, by definition, its capacity is less than the demand placed on it (late orders are bound to appear). Furthermore, as resource BROWN is scheduled to start at the beginning of the scheduling horizon (6/6), "First Day Loads" are bound to appear at the preceding resources.

The three orders of the Drum coloured in red are: product B (9/6) 2:51 h. late, product A (10/6) 1:51 h. late, and product B (10/6) 11:11 h. late.

■ Removing conflicts: obviously, no set up time can be saved because the constraint is in the part of the line where common products are produced and thus, it will be continuously processing the same part.

The user decides to automatically allocate overtime to solve the overload problem. DISASTER distributes the 10 hours of overtime (maximum weekly overtime allowed) by assigning everyday two hours to the constraint. As a consequence, only one order remains 2:01 h. late (product B 10/6). It is decided that half of the buffer is enough protection against disturbances and no further actions are taken.

■ Subordination: as it was already guessed, two "First Day Load" cases appear at the resources preceding the constraint:

| Resource | Peak size (h.) | % Buffer eaten |
|---|---|---|
| MAGENTA | 36:09 | 9:09 |
| CYAN | 32:44 | 8.18 |

The peak size, in both cases, is considerable (scheduling the batches backwards assuming resources' finite capacity, peaks are pushed backwards and accumulated in the first day of the scheduling horizon). Besides, resources cannot be offloaded (all the system is overloaded). Two different decisions can be taken at this point:

» Decision 1: the more sensible solution would be -looking at the fact that they have slightly more capacity than the constraint (catch up possibility)- to allocate *only the overtime required to avoid constraint "starvation"* (remind that two overtime hours are allocated at the constraint everyday). The user decides to apply this solution and employs the overtime option of DISASTER to solve the two FDL cases.

» Decision 2: the other possible solution is try to solve the peaks by identifying the resources as constraints and ordering the batches in an optimum manner (creating their Drums in order to exploit their available capacity in the best possible way and avoiding the utilization of overtime -operating expenses-).

■ Drum 2: resource MAGENTA is identified as the second constraint and its Drum created. Batches are sequenced so that Drum1 is never starved of parts (DISASTER takes into account previous Drums so that they are not in conflict with each other -suboptimization is avoided-). However, taking into account that Drum1 was scheduled from the first day of the scheduling horizon and it had two more hours of overtime allocated each day, three batches of MAGENTA are scheduled to start in the past. This causes three "Fixed Drum Violation" cases (see Drums next page):

1- 10 min. Drum violation in batch A-8/6. Three possible solutions can be taken at this point: allocate overtime, offload some of the parts to another resource, or move Drum1 forwards (creating more late batches) to locate the batches in the past of Drum 2 in the present (the user initially tried this last option but as a result most of the final products due dates were missed by considerable time -the Goal of maximizing throughput was in high jeopardy-). It is finally decided to allocate overtime to solve the Drum violation conflict (DISASTER automatically allocates 1 hour to solve a late peak of 10 min.).

2- 3:15 hours Drum violation in batch B-7/6. 4 hours of overtime are allocated to solve this conflict (for the 6/8 the working day is formed now of 12 hours).

3- 4:20 hours Drum violation in batch A-7/6. DISASTER does not allow to allocate more overtime and the user decides to offload this batch to a less overloaded resource (although all of them are bottlenecks). It is offloaded to resource BLUE.

No more Drum violation conflicts arise and the three batches initially located in the past are now placed in the present (it has to be noticed that from the initial 36:09 h. peak, once the Drum was created, only three batches with a total amount of less than 8 h. load had to be resolved -in contrast to decision 1, overtime was saved by synchronizing both interactive constraints-).

■ Subordination 2: the rest of the system is subordinated to Drum 2 and, as it could be predicted, the peak of 32:44 of resource CYAN still remained unsolved. The user decides again to relocate its buffers in order to synchronize them with the two previous Drums. Resource CYAN is thus identified as the third constraint.

■ Drum 3: when the Drum is created, DISASTER warns the user that -as in the last case- there are batches that are in conflict with previous Drums and have to be solved before progressing with the scheduling process. The "Fixed Drum Violation" cases are (see Drums next page):

1- 1:43 h. Drum violation in batch A-8/6. DISASTER does not allow to allocate overtime (all permitted overtime allocations for the first day of the scheduling horizon has been spent in the two previous constraints). The user then decides to offload the batch to resource GREEN.

2- 2:22 h. Drum violation in batch A-7/6. The parts are offloaded to the resource with higher relative capacity: RED.

3- 2:17 h. Drum violation in batch B-7/6. The batch is offloaded again to resource RED.

As in the previous case, the 32:44 h. peak has been solved by transferring the load of the first operations in the route to those at the end (that would be idle anyway at the beginning of the scheduling horizon). However, as there is lack of overall capacity, conflicts in the subordination process caused by the offloading decisions can be predicted.

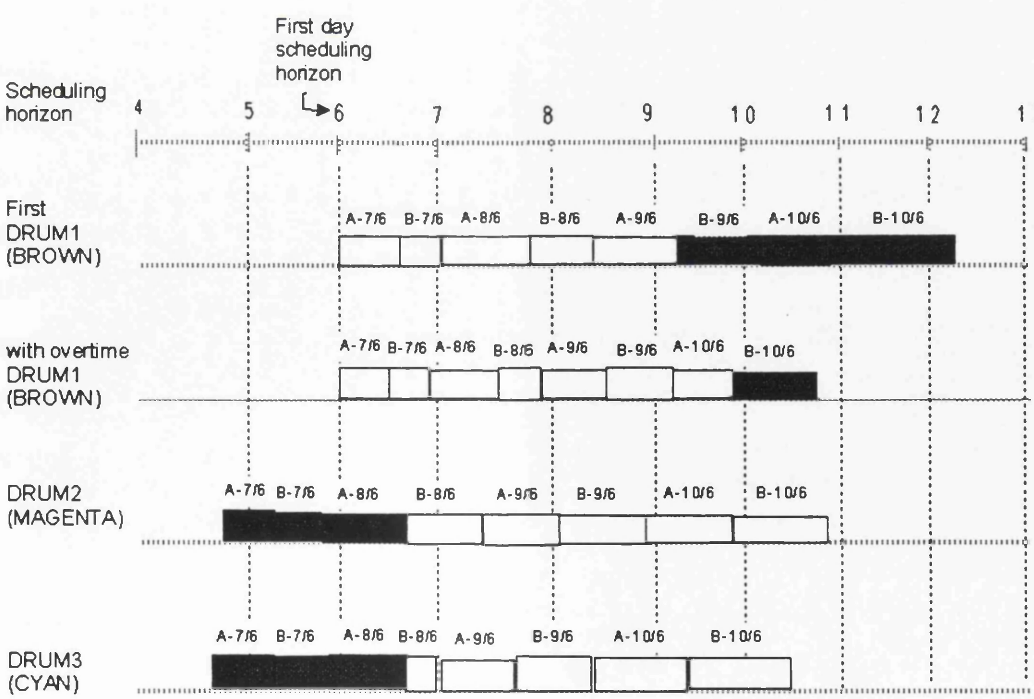
■ Subordination 3: three minor "First Day Load" cases take place in the three resources at which parts have been offloaded (the three of them have peaks of slightly more than 4 hours). Overtime is allocated to solve the three conflicts (it has to be noticed how DISASTER did not allow allocate overtime for resource CYAN when it was identified as the third constraint, and at the subordination stage -as in decision 1- does not consider any limitations in allocating overtime).

■ Final results:

» Decision 1: the product release and material diverted points are scheduled as follows:

| Station | Processing date | Quantity |
|---|---|---|
| A1 | 6/6 | 210 |
| A4 | 6/6 | 20 |
| B4 | 6/6 | 15 |
| A4 | 7/6 | 25 |
| B4 | 7/6 | 20 |
| A4 | 8/6 | 30 |
| B4 | 9/6 | 30 |
| A4 | 10/6 | 30 |
| B4 | 10/6 | 40 |

» Decision 2: the three Drums -before the Drum violation conflicts were resolved- in 2-nd and 3-th constraint are (when all the conflicts were solved, the material release dates for resources MAGENTA and CYAN were scheduled for the first day of the scheduling horizon).



(C) Operational features

The same overtime issue of case 3 takes place in Decision 1. As the peaks of 36:09h. (MAGENTA) and 32:44h. (CYAN) are caused by the same product DISASTER locates them as a single batch and automatically assigns all the overtime required to solve the load peak (it does not allow the user introduce only the overtime needed to maintain the constraint constantly busy). The allocation of 36 and 32 hours at the first scheduled day is, on one hand, impossible, and on the other, unnecessary (looking at the characteristics of the case).

(D) Schedules feasibility

Initially, due to the lack of overall capacity, unless actions are taken to increase resources' available capacity, the system will not be able to answer all the demand placed on it. Without interruptions, resource BROWN would produce 171 products -in the scheduling horizon-; while total demand is for 210. With the 10 hours of overtime, it would be capable of answering demand assuming that (a) it is never "starved", (b) disturbances do not affect it, and (c) the products are shipped as soon as they are processed at the constraint.

Unfortunately, none of the three assumptions is correct for this model: (a) according to the Drum of the CCR (see Figure above), the constraint is scheduled to start just at the beginning of the scheduling horizon; but the parts still have to be processed at the two upstream resources (see Drum 2 and Drum 3 in Figure above). (b) Production disturbances do exist in the system and, as the CCR has not any slack time -is busy all the time-, all the time lost due to disruptions represents a lost in throughput. (c) There are still products scheduled in the CCR one hour before the end of the scheduling period (assuming overtime is allocated); therefore, unless overtime is also allocated in the succeeding resources, products would not be able to be shipped on time.

On the other hand, examining the non-constraints' schedules, the same resource is scheduled the same day at two different stations. However, following the rule of processing the parts in the same order they reach the resource, no further problems will appear (although initially shop floor personnel could be confused looking at the schedule).

(E) Objectives achievement

In a close to balance system with lack of overall capacity, throughput can only be increased if constraints' available capacity is increased. But, taking into account that the system is close to balance, this action will only move the constraint from one part of the system to another. Therefore, unless capacity is increased at all the resources simultaneously, throughput will be lost.

The model was simulated according to two different schedules:

1- Processing first all products A and without allocating any overtime. As a result, all A and 61 B were shipped (a total of 166).

2- Following DISASTER's schedules, introducing process times fluctuations, and without allocating any overtime. The result was 75 A and 89 B products shipped on time (a total of 164).

The only difference of two products is due to the utilization of the excess capacity of the downstream resources in setting up (instead of being idle waiting for the parts coming from the constraint).

In the two cases all demand could not be answered. In the first case, the constraint was focused on producing A and utilizing the remaining time to produce B. In the second case, the constraint followed the orders' due dates to answer demand. The selection of the strategy to implement will be first guided by the necessity to meet due dates, and then, according to products' profitability analysis (if product A brings more net profits than product B, then throughput capacity should be utilized first to produce A and then to produce B).

Additionally, overtime utilization is encouraged whenever results on a throughput increase. In close to balance environments, overtime should be carefully allocated or otherwise the constraint will wander along the system. In our case, allocating the necessary overtime at the constraint and then allocating the overtime required to process constraint's parts and feed the CCR, the 210 products' demand could be answered. DISASTER only suggested employing overtime at the constraint and at the preceding resources, overlooking the succeeding ones. This action, will move the constraint downstream, and increase WIP there without improving due date performance.

(F) Immunization against disturbances

In section 8.3 was pointed out how in close to balance systems the effect of production disturbances spread rapidly along the system and leads to a lose of throughput. The current case is an example of this situation and throughput is lost when Murphy affects any of the resources of the model. Buffers and protective capacity are not enough when all the resources of the system have to work at full capacity during the whole scheduling period in order to answer demand.

CASE - 5 > **A system with unstable demand**

Final products' demand is normally subject to changes from the customers. Hardly ever a single standard product is ordered for the same quantities for long time periods (if the product mix does not change, the number demanded may suffer variations -i.e. production line and continuous processes-). However, the most common situation is when not only the quantities demanded change, but also the product mix suffers alterations. This circumstance occurs, for example, in (a) make-to-stock, batch production environments, (b) production systems containing a large final products catalog, and (c) make-to-order, jobbing manufacturing systems.

The main consequence of regular changes in demand is the continuous necessity to change the production plans and schedules. From one scheduling period to the next, the constraint of the system may have drastically changed, and its exploitation efforts have to vary accordingly. Each time, production schedulers and shop floor personnel would have to obtain the maximum output from the identified constraint (create the optimum schedule and subordinate everything else to it) and do not let inertia be their constraint.

(A) Model description

Two different production situations caused by different production demand will be compared in this case. The same model of Case 2 will be used (NET141), but with different final product mix.

The orders are distributed as follows:

| CASE | Product | Number of orders | Total quantity |
|---|---|---|---|
| A | B | 4 | 46 |
| A | D | 4 | 53 |
| A | H | 3 | 28 |
| A | F | 2 | 20 |
| B | B | 2 | 45 |
| B | D | 4 | 100 |
| B | H | 2 | 20 |
| B | F | 2 | 15 |

The principal difference between case A to case B is the increase of product D demand from 53 to 100 units.

(B) Scheduling process

- Identification: the load/capacity ratio for both situations is:

| CASE A | CASE B |
|---|---|
| RED ----- 95% | BLUE ---- 107.81% |
| MAGENTA - 78.08% | MAGENTA - 95.63% |
| BLUE ---- 68.85% | RED ----- 75.35% |
| BROWN --- 62.36% | BROWN --- 50.87% |
| CYAN ---- 20.71% | CYAN ---- 23.48% |
| GREEN --- 11.90% | GREEN --- 11.99% |

- Case A contains overall excess capacity and a severe CCR that is not a bottleneck.

- Case B contains a severe CCR that is a bottleneck.

- Ruins: in case A, 3 blocks are placed one above the other in the ideal schedule at certain times; while in case B, 4 are sometimes placed.

■ Drum:

- Case A contains only one batch 10 minutes late. No actions are taken to remove this minor conflict.

- Case B on the other hand, contains 8 late orders that sum in total 38.5 h. of delay. This conflict is removed assigning automatically 11 hours of overtime. As a result, only one order remains late for 1:36 h. (as only 20% of the buffer is eaten, no further actions are taken).

■ Subordination: no conflicts take place in case B, and the outputs are generated. In case A, a "First Day Load" situation appear with resource BLUE. The 2:58 h. load peak is solved assigning overtime to that resource. No more problems emerge and the output files are also generated.

(C) Final comment

The production situation in an environment with unstable demand can radically change from one scheduling period to another. In the current model, a slight difference in customers' demand originated to different situations: (a) overall excess capacity in case A, and (b) a severe bottleneck in case B. If a different demand would have been placed, any of the previously studied 4 general production circumstances could have been occurred. The user of DISASTER may face in one production period a scheduling process where conflicts can be easily removed (e.g. current case B), and in the next period be immersed in the laborious task of solving major problems (e.g. Case 2).

Long term improvement efforts focused on the constraint (e.g. process time and setup time reductions, engineering efforts to increase the available capacity, changes in product design, Buffer Management utilization to identify and solve the major source of production disturbances, etc..) are sometimes futile in production environments with unstable demand. Furthermore, in environments like this, workforce relaxation can be the principal constraint to achieve the POOGI implementation.

<u>CASE - 6</u> > **A system with stable demand**

As opposite to the above case, a manufacturing system characterized by a fairly stable demand facilitates the implementation of production improvements by focusing on the critical parts of the system. First of all, all efforts should be focused on increasing constraints' available capacity (in the case of a bottleneck resource, a capacity increase would mean an increase in global throughput). Secondly, schedule similarities from one period to another, would lead to acquire the necessary expertise to plan and control production in the best possible manner (i.e. utilizing minimum protection -inventory- against disturbances, reducing operational expenses to meet the schedules -overtime-).

DISASTER, can be a useful tool in this search for the optimal schedule that would maximize throughput by simultaneously minimizing inventory and operating expenses. With the appropriate experience, the initial parameters can be accurately set and the conflicts properly handled.

Nevertheless, increasing constraints capacity would only replace the current constraint for a new one. At this point, the schedules, improvement efforts, and the entire system would have to centre the attention on the new constraint. DISASTER can aid again in the search for the best schedule and support strategic improvement decisions. DISASTER can be considered an essential part of the POOGI that leads the company towards the Goal.

*** Sensitivity to initial parameters**

The way DISASTER's parameters affect the schedules produced is:

» <u>Scheduling horizon</u>: the orders to be included in the schedule are restricted by the start and end dates of the scheduling horizon. There may be orders and forecasts for the next two months, but the user may only wish to create schedules for the next two weeks. Or, on the contrary, all the orders to be produced may be loaded to DISASTER and then the user may use the software to determine the scheduling period -in order to identify CCRs and determine the required capacity at key resources- (not very common when due dates are the production driving force, but possible in some make-to-stock situations).

In any case, the scheduling horizon represents system's available capacity. Any change in the scheduling horizon, will modify the whole production situation (e.g. with a short scheduling horizon the system would be overloaded and many bottlenecks would appear; while with a long scheduling horizon the system would have plenty of capacity and no conflicts would arise in the scheduling process).

» Buffers' length: Case 1 model is used to analyze the effect three different buffer sizes applied in the same situation have in the final schedules:

- Case A: constraint, assembly and shipping buffers are of 8 hours. As a result, the last part is scheduled to leave the constraint 8 hours before being shipped. The 8 hours shipping buffer pushes backward the whole Drum; so, the first part is scheduled only 30 min. from the beginning of the scheduling horizon. DISASTER in this situation warns the user that there is not enough time for the parts to be processed at the preceding resources by creating two "First Day Load" cases.

- Case B: the three buffers are set in 4 hours. In this case, the first part is scheduled to start processing at the constraint 4 hours after the start of the scheduling period. In the subordination process, a "First Day Load" case occurs. With four hours of constraint and shipping buffers, the parts seem to have enough time to reach the constraint (after the FDL conflict is solved) and to be shipped on time.

- Case C: only 1 hour is determined for the three buffers. The parts are scheduled to start processing at the CCR 7:30 hours after the material is released to the plant, and leave the constraint only 1 hour before shipping. No conflicts occur in the subordination process. However, with such small protection after the items are performed in the CCR, there is a high risk for the schedule of being affected by production disturbances.

As it has just been shown, the complexity of the scheduling process is highly influenced by the size of the buffers. A wrong buffer size can make the schedule impossible to be followed in the shop floor. The user must be careful in determining the buffers length because they represent the only way the critical parts of the system are protected against disruptions. Furthermore, whenever the constraint changes its location (e.g. as a result of demand instability), buffers have to be modified accordingly.

» Work hours per day: this parameter determines the number of hours the resources of the system are available. It is a default value that is only operational when the "calendar.lib" file is not present at the beginning of the scheduling process. When this occurs, the capacity of the system is defined, on one hand, by the scheduling horizon, and on the other hand, by the work hours per day introduced in this field.

» Overtime: three parameters determine the maximum overtime DISASTER allows to allocate automatically to solve capacity conflicts: (a) daily overtime (the maximum amount of overtime DISASTER is allowed to schedule on any day), (b) weekly overtime (the maximum total amount of overtime that can be employed from Monday to Friday), and (c) weekend overtime (the maximum amount of overtime the system can schedule over the two weekend days).

Overtime represents one of the principal features the user can employ to solve temporary overloads (red blocks are rapidly removed with this option). However, he/she must be confident that the overtime allocated to a particular resource can be carried out in the day determined. Additionally, overtime must be accurately set, otherwise, it can cause fatigue and dissatisfaction in the shop floor personnel.

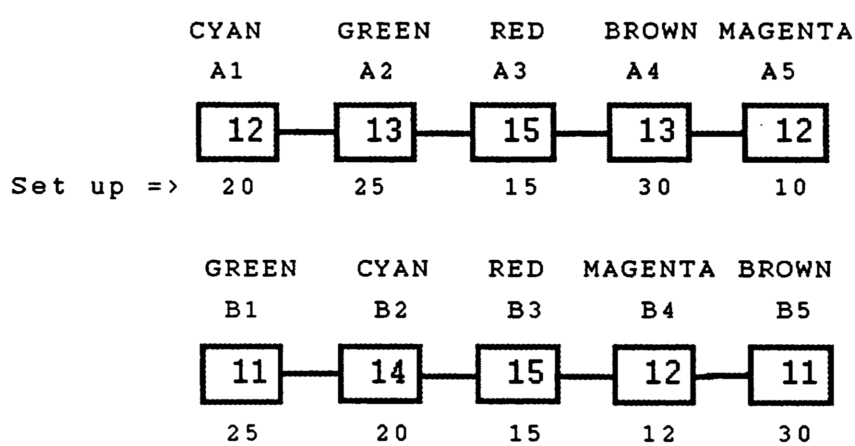
» Protective capacity: this parameter determines the percentage of capacity for any non-constraint resource that remains unscheduled so that catch up possibility can be employed to solve the impact of production disturbances. It is, with the time buffers, the protection mechanism DISASTER utilizes to safeguard schedules from the unpredictable production disruptions. The protective capacity parameter is a default used for every resource that has not this value defined in the resources input file.

To analyze the effect of this parameter, Case 5(B) model was initially scheduled with a 5% of protective capacity. The FDL situation that took place showed a peak size of 1:52 hours. The same model was then scheduled with a 15% of protective capacity. This time, the FDL contained a peak of 4:16 hours (all the constraint buffer was eaten). As can be seen, the protective capacity value reduces non-CCRs capacity and influences the scheduling process. Therefore, it should be individually determined according to the characteristics of each production resource (i.e. number of breakdowns, process and set up time variability, number of tool failures, etc..).

*** Shop floor common practices**

Shop floor common practices embrace the actions taken in the shop floor in order to (a) follow the schedule and achieve the scheduling objectives (e.g. batch overlapping, constraint offload, overtime, set up savings), (b) protect the schedule against production disturbances (e.g. time buffers, inventory buffers, protective capacity, etc..), and (c) represent shop floor typical policies and situations (e.g. minimum/maximum batch sizes, maintenance or quality inspections, more than one vendor for the same part, etc..). These common practices can be located in a lower stage under the framework of the just analyzed general production situations. The following features comprise the commonly utilized shop floor practices and the way DISASTER contemplates them.

» Batch overlapping: it has been shown in previous models that DISASTER assumes batch overlapping as a normal shop floor practice (otherwise, according to DISASTER's builders, a policy constraint would exist that should be broken before installing the software). DISASTER does not establish any transfer batch size. It only creates the constraint and material release schedules and leaves the task of following them in the hands of shop floor personnel. To demonstrate this fact, a simple model containing two final products and formed of two production lines has been produced.



Production demand is formed by four orders for each final product to be performed under the following conditions (note that two different cases are analyzed by modifying the buffer lengths):

- Scheduling horizon: start> 6/6 ----- end> 10/6
- Buffers length: case A> all of them 2 hours
  case B> all of them 4 hours
- Overtime allowed: daily>2h., weekly>10h., weekends>0h.
- Protective capacity: 5%.

Resource RED -loaded at 84.38% of its capacity- is identified as the first constraint of the system. The next one in the load/capacity list is resource CYAN with 72.08%.

The Drum for resource RED contains the following first and last batches dates for both cases:

Case A: first batch> 6/6 at 2:14 (10 units) ---- last batch> 10/6 at 5:59 (20 u.)
Case B: first batch> 6/6 at 0:14 (10 units) ---- last batch> 10/6 at 3:59 (20 u.)

Two "First Day Load" conflicts are solved in the subordination process by allocating overtime.

The material release schedule is in both cases:

| Material | Date | Quantity |
|---|---|---|
| B | 6/6 | 15 |
| B | 6/6 | 10 |
| A | 6/6 | 15 |
| A | 6/6 | 10 |
| A | 7/6 | 25 |
| A | 7/6 | 30 |
| B | 8/6 | 10 |
| B | 9/6 | 20 |

The conclusions that can be drawn from DISASTER's schedules are:

1) The Drum of case A can only be accomplished assuming that batches can be overlapped: the first part is scheduled the 6/6 at 2:14, while assuming that process and transfer batches are equal, parts would only be available at the constraint the 6/6 at 4:45. Similarly, the parts of the last batch processed at the constraint would only reach shipping on time assuming batch overlapping.

2) In case B, the 4 hour buffers defined make impossible the processing on time of the first batch scheduled at the constraint (another example of the sensitivity to parameters): assuming unit transfer batch, the first part will be available at the constraint the 6/6 at 1:10; while DISASTER unrealistically schedules this batch to start the 6/6 at 0:14 (DISASTER informs the user of this fact by a footnote on the screen). This "First Day Load" conflict is resolved by allocating overtime at the two resources preceding the constraint.

3) In addition, shop floor personnel is confronted with the dilemma of which of the 4 different parts scheduled to be released the same day produce first. Without the constraint schedule, this can originate the release of the products in the wrong order, and thus, miss production due dates.

» Substitution of machines (production offload): resource capacity problems are normally solved by offloading some of the parts scheduled in one resource to another less saturated one. DISASTER allows offloading the parts of the selected constraint's batch to any other resource in the system. However, this possibility is only available for the resource identified as a constraint.

» Overtime allocation: this common shop floor practice included in DISASTER has been thoroughly analyzed and criticised in previous models. It has to be mentioned that the allocation of overtime -under certain limits- can be performed manually or automatically, and only at the CCR or at a resources that creates a conflict in the schedule (i.e. constraints, "First Day Loads", and "Red Lane Peaks").

» Set up time savings: the automatic and manual set up saving options of DISASTER only apply to the constraint resources and when the batches to be "glued" process the same parts. DISASTER assumes that the rest of the resources contain excess capacity and that this excess capacity is available for set ups. Two different cases are overlooked by this option:

1- The case in which the system contains several bottlenecks (lack of capacity): shop floor personnel in this situation will normally try to save set up time at all the bottleneck resources; while DISASTER would only give the possibility of saving set ups at the bottlenecks identified as constraints (the only solution is sequentially identify all of them as constraints).

2- The assumption of "gluing" only the batches that process the same parts overlooks the possibility of saving set ups by "joining" the batches of different parts that have the same set up procedure (e.g. drilling of holes of the same diameter in different pieces, cutting pipes of different thickness or diameter in the same measures, etc..).

» Batch splitting: batches will normally be splitted when the scheduler does not consider appropriate to create individual orders to represent different customers' demand or divide the batches in small lots to be sent to the customer (have different due dates).

The batch splitting option of DISASTER can only be applied to the batches of the resources identified as constraints. In real practice, batch splitting is performed according to individual product requirements and not to particular resources. Therefore, DISASTER will not be a good supporting tool for the cases in which the batch to be splitted is not processed at the constraint.

The model used to analyze batch overlapping has been employed to check the effects of this option. It has to be noticed that once the batch has been splitted, the new batches act as independent production orders: if they are rescheduled, on one hand, their set up time is added to the resource load, and on the other hand, material release schedules contemplate both batches independently.

» Production disturbances (unexpected circumstances): there are many unpredicted situations that affect the schedules and may cause late orders' delivery. The way DISASTER addresses the different factors that disrupt the production flow and affect the schedules is:

A) Machine breakdowns, tool failures, personnel absenteeism, stochastic process and set up times, and product transport delays between operations: by definition, non-constraint resources' excess capacity allows them the production "catch up" possibility. On the other hand, any production disturbance that affects the CCR will lead to a lost of throughput whenever the constraint is a bottleneck. DISASTER protects the Drum by using Time Buffers in front of the key points and protective inventory at the non-constraint resources.

However, according to the way DISASTER creates the schedules based on the final products due dates, whenever the constraint resource is not a bottleneck, the Drum will contain "gaps" -slack time- (periods of time in which the constraint is idle). This idle periods provide the excess capacity required to offset the effects of the production disturbances and allow the order to be shipped on time.

B) Change in the market requirements or urgent new orders: when changes in scheduled due dates or quantities occur, DISASTER gives the possibility of modifying the initial data and create a new Drum in a very short time. Nevertheless, these changes may originate further conflicts that would have to be solved.

C) Predicted scrap or yield: DISASTER's arrow input file contains a field for this aspect. Whenever there is a predictable loss of material between two stations, the predicted percentage of material loss can be entered in this variable.

D) Unpredicted scrap and "stealing": when products are unexpectedly lost during the production process and expediting or rework is required, the scheduler faces the situation in which unpredicted products must be included in the existing schedule. This will originate the necessity of creating new orders or modifying the existing ones, and starting the whole scheduling process again.

E) Vendor late or faulty products delivery: when vendor's delivery time excess the time defined in the Raw Material file, the batches affected must be rescheduled. This rescheduling can be done manually or restart DISASTER from the beginning (the new conflicts that may arise would have to be solved again).

» Minimum/maximum batch sizes: the policy of defining minimum and maximum batch sizes is a normal practice in some production situations. For example, minimum batch sizes are sometimes defined in furnace process stations or painting installations. On the other hand, there are still some make-to-stock plants in which the minimum and maximum batch sizes are determined according to the size of the containers.

DISASTER equals the process batch to the production order and does not make any distinction between process and transfer batches (as it was said before, it assumes batch overlapping and leaves the task of determining the size of the batches to shop floor personnel).

» Particular inventory locations: inventory buffers are normally located in front of key points (e.g. capital intensive machines, constraints, assembly operations, etc..). DISASTER, apart from the shipping, constraint and assembly buffers, includes the possibility of defining buffers between any selected stations. These last buffers will not have any effect if the place in which they are located is an assembly, constraint or shipping point (in this case the size of the buffers defined in the parameters will be used to create the schedules).

» Space limitations: in many cases, the space in which locate inventory is limited is some places of the system. This becomes a major problem that should be taken into account by the scheduler. DISASTER does not contemplate this problem and creates the Drum and the material release schedules assuming that no space limitations exist in the plant.

» Predicted maintenance or 'briefing' stoppages: when the stoppage affects the whole plant, the best thing to do is modify DISASTER's plant calendars before starting the scheduling process. On the other hand, if the stoppage only affects a few resources, then the particular resource calendars are the ones that should include the predicted stoppage.

» Predicted destructive quality inspection: if it is known "a priori" that the product quality analysis ruins the item, this can be included as scrap in DISASTER's arrow file.

» More than one vendor for the same raw material: a normal practice in some companies is to buy different percentages of the same part to more than one vendor (so that they can play with prices and guarantee the availability of the material in the future). If all the vendors for the same part have the same delivery time, then DISASTER would not have to make any raw material distinction. Otherwise, (a) different names should be given to the raw materials (not recommended solution due to the control difficulty that would suppose), or (b) the same name and the longest delivery time is set in DISASTER (this would lead to excess raw material inventory for the parts delivered earlier than the time defined).

» Vendors deliver in different lots: when the vendors do not deliver all the material in a single lot, the scheduler faces the situation of (a) wait until the last batch has arrived and produce the whole order (in this case the delivery time will be the one determined by the longest lot to arrive), or (b) split all the batches according to the material deliveries (this will originate several minor batches for the same product to be scheduled independently).

### 4.4 - Special production cases

There are many other special production situations that can be added to the above cases. These particular production situations complicate the schedule generation and sometimes require specific solutions to be applied. The following points summarize some of these cases and contemplate the way DISASTER tackles them.

» Different lead time from the constraint to shipping: this circumstance occurs when the constraint is located in different places in the products' route and has different lead times from its location to shipping. An example of this case can be found in the model utilized in Case 1 of "general production circumstances" section. Resource GREEN was the resource identified as the constraint of the system, and from station A3 to shipping, 30 minutes are required for a single unit -without set up time- to be processed at the three remaining operations. While from stations E3 and G3 only 20 minutes are needed.

This situation acquires more relevance when the completion time differences are considerable (e.g. several hours). In these cases, the initially defined buffers may be considered excessive for some products and insufficient for others. For example, for a product that only requires 4 hours from the constraint to reach shipping, a 3 hours shipping buffer may be considered excessive in order to handle production disturbances. On the other hand, a 3 hours buffer may be insufficient for a product that requires 24 hours till final completion.

DISASTER, by including a single buffers for the stations of the constraint resources ignores this situation. A possible solution to this problem is to change manually the production sequence of the batches by taking into account the total completion time required (working first on the batches that require more time to be completed).

» A constraint producing more than one part for the same product: this situation arises when the final product route contains more than one part processed in the constraint resource. In this case customer due dates will not serve as guidance in sequencing the production batches since all the parts have the same due date.

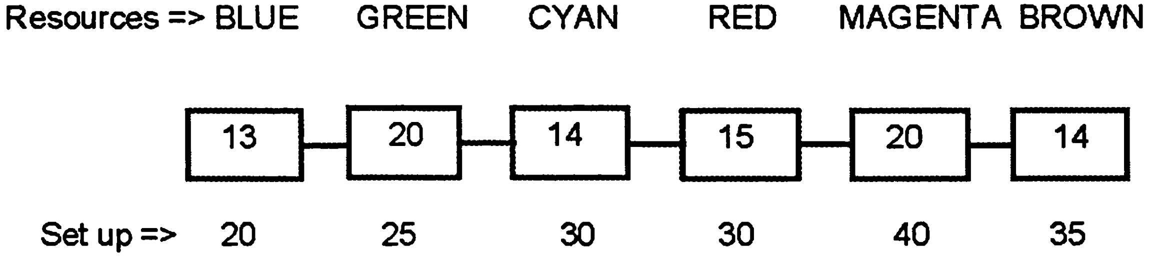
This case also takes place in the above model (stations E3 and G3). Here, both stations produce different parts that are assembled in the succeeding operation and they both contain the same completion time from the constraint to shipping. DISASTER uses the operation processing time to schedule their batches (the batch with less processing time -G3- is scheduled first). The production sequence would have a decisive influence in the plant performance if the completion times from the constraint to shipping of the products processed in both stations were considerably different (above case).

» Particular constraint locations: sometimes the constraint can only be identified when DISASTER is runned and the load/capacity list created. At this point, the user may realize -for example- that the constraint is located at the beginning or end of the process, and will probably be compelled to modify the buffers length.

An example that illustrates this circumstance can be found in the production line model employed in Case 3 of "general production circumstances". In that case the constraint -resource RED- was located in the middle of the line and all the buffers were defined to be 4 hours. If instead of resource RED, resource BLUE (first resource of the process) was the system's constraint, then the 4 hours constraint buffer will be erroneous, and the shipping buffer probably insufficient. The same situation occurs when the constraint is the last operation of the process and, as a consequence, buffer sizes would only be able to be accurately defined once the constraint position is identified.

» Interactive constraints: this situation takes place whenever one constraint resource feeds another constraint resource. In such a case, following market's due date sequence at one of them may cause "starvation" -and, maybe, a throughput loss- in the second constraint.

The production line of the above case has been modified (as it is shown in the figure) to create a interactive constraints situation.



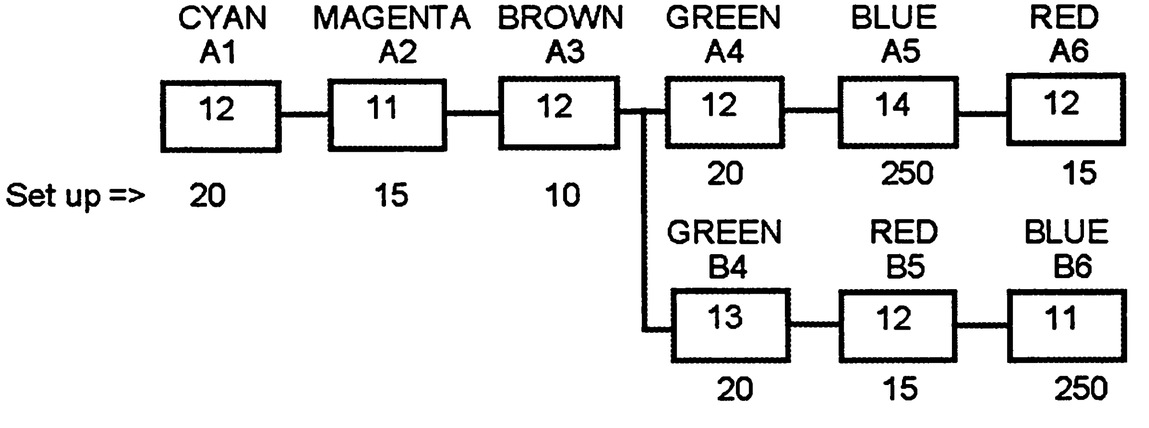

Resources GREEN and MAGENTA are both loaded at 100% of their capacity and contain a 4 hour constraint and shipping buffers. Any of them can be selected as the initial constraint (having the security that conflicts with the other constraint will appear in the subordination process).

The user decides to select resource MAGENTA as the initial constraint. After solving minor problems in the Drum, resource GREEN -as was expected- exhibits a major "First Day Load" conflict. The user decides to choose this resource as the second constraint. A rod of half buffer (2 hours) is automatically placed by DISASTER between the two constraints to handle production disturbances. The scheduling process finishes when a "Fixed Rod Violation" conflict with the first batch is solved by allocating overtime, and two other minor "First Day Load" cases are solved.

DISASTER is a useful tool for solving interactive constraint cases due to its iterative scheduling procedure: DISASTER, will only produce final feasible schedules when all the conflicts between the resources of the system are solved.

» Long set up times: in most of the plants there is always one or a few resources characterized for long set up times. In the following two cases it is shown the way DISASTER tackles this problem when large set up times affect a constraint resource (situation 1) and a non-constraint resource (situation 2).

■ Situation 1 > the model used for this case is basically the two branches production line employed in Case 4. Production demand and set up times have suffered minor changes to accommodate the model to the actual case: product A contains a demand of 95 units distributed into 4 orders, and product B contains 85 units also in 4 orders. The model with the process and set up times is shown in the figure.



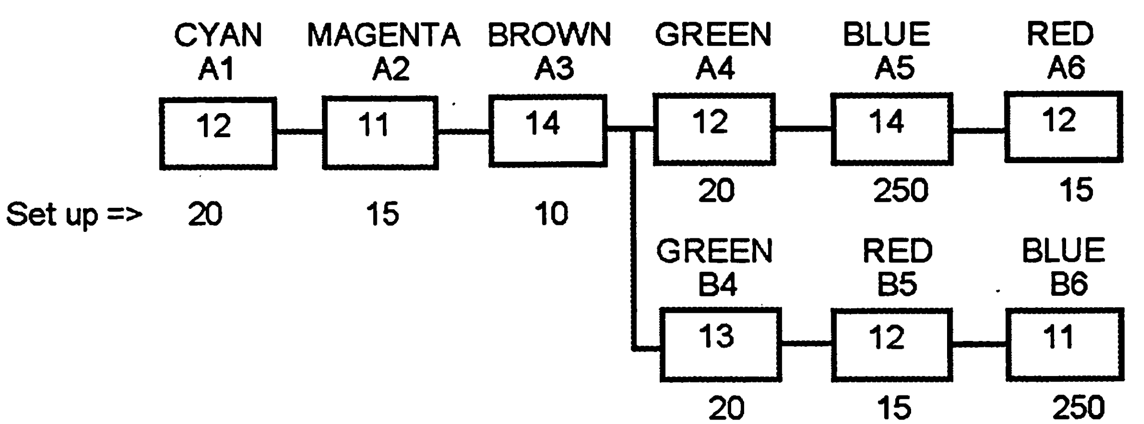

Resource BLUE, loaded at 94.38% of its capacity, is identified as the first constraint. It has to be mentioned that DISASTER does not include the set up time in this load/capacity list. Taking into account that resource BLUE contains 250 min. of set up time, capacity problems can be predicted once the schedule is created.

The batch sequence shown in the Drum confirms the initial predictions: according to the orders' due dates the batches are sequenced alternatively (A-B-A-B-A-B-A-B). As the resource needs setting up for each batch, the real load is:

("A" total orders quantity * process time) + ("B" total orders quantity * process time) + (number of orders * set up time) = (95*14)+(85*11)+(8*250)= 71:08 hours of total load. Being the resource capacity of 40 hours, the resource is then loaded at 177% (71/40) of its capacity.

It can be seen, the initial resource load estimations can radically change once the Drum is generated. The user now faces the dilemma of (1) following the Drum and meet the established due dates, or (2) save set ups by grouping together all the orders for the same products. If the first decision is taken, the user will have to apply DISASTER's overtime or offloading options. On the other hand, if the second solution is followed, using DISASTER's set up ratio option, the user will be able to group all the orders and save 25 hours in set up (of course, with the price of missing due dates).

■ Situation 2> changes in the above model's process times are performed to create the situation of a non-constraint resource with long set up time (see resource BLUE in figure).




Demand placed on the system is the same as in situation 1, but in this case resource BROWN (with a load/capacity ratio of 105%) is identified as the first constraint. Resource BLUE is -as in the above case- loaded at 94:38% of its capacity.

The Drum for resource BROWN is created and the rest of the system subordinated to it. As could be expected, the subordination process generates 4 major cases of "Red Lane Peaks" at resource BLUE. Selecting this resource as the second constraint, and creating its Drum, the same situation of the above case arises: the batches are sequenced alternatively so that no set up time can be saved, and therefore, most of them are late.

Additionally, DISASTER does not allow the possibility of saving set ups by grouping the batches, because this would violate the first Drum. The user can only (a) allocate large amounts of overtime or offload the resource, (b) loop back to the first Drum and put the batches of the same product together, or (c) change the initial due dates -grouping same products- and start the scheduling process again.

» Resources with unpredictable process times: one of the causes of process times unpredictability is originated by unreliable resources. This unreliability normally takes the form of machine breakdowns or tool failures. Additionally, the same situation occurs when the process times contain large degree of fluctuations (e.g. a workforce dominated environment in which workers' skills influence greatly in the operations completion times). As a result, in both cases standard process times cannot be trusted and the effects of negative fluctuations may spread along the system.

Process time unpredictability is sometimes tackled by inflating the process time value introduced in the computer: this creates schedules that are safeguarded against production disturbances but that are unrealistic (e.g. the case of MRP). DISASTER -like all the other scheduling packages- only allows the introduction of a single process time for each station; but instead of having to inflate the process times to address the production disturbances problem, it provides the time buffers and protective capacity options.

The user of DISASTER will be able to rapidly change the buffer lengths and create new schedules for those cases in which a resource with unpredictable process time is spotted. For example, he/she can increase the constraint buffer when the major source of disturbances is placed before the constraint, or increase the shipping buffer when is placed downstream the constraint. Additionally, inventory buffers can be placed in front of individual resources.

Finally, DISASTER's resource input file contains an optional field in which specific protective capacity values can be defined for each resource. In the case of very unpredictable process times, the protective capacity value of the resource can be increased so that one part of the resource's capacity remains unscheduled to offset the effects production disturbances.

» Fixed process sequence / dependent setups: set up times are sometimes dependent on the process sequence. For example, in the production process of generating pipes from steel rolls, a range of similar diameter pipes would be produced without changing the cylinders employed to fold up the steel. If highly different diameters pipes are alternatively scheduled, the time required to set up the work centre would be much greater than if the pipes of similar diameter are arranged together. DISASTER's version 1 does not contemplate this situation (a single set up time is defined at each operation) but latest versions include the dependent set up option. This option would allow major set up savings by ordering the batches by family.