SYNCHRONIZED MANUFACTURING AS IN OPT: FROM PRACTICE TO THEORY

BOAZ RONEN and MARTIN K. STARR[1]

Tel Aviv University, Faculty of Management, Graduate School of Business Administration, Tel Aviv, Israel and [1]Columbia University, Graduate School of Business, New York, U.S.A.

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Abstract—Synchronized manufacturing as in the OPT system (Optimized Production Technology, by Creative Output Inc.) is a relatively new concept for production management.

This paper analyses the nine OPT rules, the OPT concepts and OPT philosophy in order to establish an analytical, theoretical basis for the OPT system. The analysis is based on systems theory concepts, mathematical programming theory and techniques, as well as queuing theory, the Pareto rule, and the Japanese production experience.

It is shown that the OPT rules reflect substantial integration of well established MS/OR techniques with the whole OPT philosophy. The paper analyzes the OPT classification of VAT plants and the Drum–Buffer–Rope concept used in OPT.

Our analysis makes a clear distinction between BIG OPT (the management system) and its subsystem SMALL OPT (the scheduler). The paper suggests that while the BIG OPT concepts may be applied in all types of processes, job shop processes and very complex assembly lines are the most suitable ones for the SMALL OPT scheduling system. The paper then shows the management by constraints methodology as a natural enhancement of the OPT concepts.

1. INTRODUCTION

Synchronized manufacturing, as achieved by the OPT system (Optimized Production Technology, developed by Creative Output Inc.) for production management, was first introduced in the United States at the end of the 70s. Since then, more than 100 papers, reviews and other publications have been devoted to the new approach. Some of them are internal training papers, books or reports published by Creative Output Inc., or by its founders or employees [1–5]. Other references explain the principles of OPT [6, 7]. Some papers deal with successful installations [8]. Others compare the OPT concepts and usage to the Japanese Just-in-Time (JIT) philosophy, or to MRP (Manufacturing Resource Planning) [9, 10], or suggest the OPT system as an enhancement of MRP II [11]. A view of OPT as a manufacturing system was presented by Jacobs [12]. Bacon and Chondhari [13] provide an interesting study comparing OPT and other systems.

This paper (which consists of five parts) covers new ground. It investigates the nine OPT rules as well as the OPT concepts and principles. It then goes on to show that the theoretical fundamentals of OPT can be identified with basic models of management science, operations research, decision sciences, operations management and systems theory.

Thus, the accomplishments attributed to OPT can be shown to be based on known theories, at least in many cases, and future research can be directed to affirm this hypothesis. The analysis makes a distinction between the OPT strategic managerial principles (hereafter BIG OPT) and the OPT scheduling mechanism (SMALL OPT). Following this analysis, three main conclusions are drawn: First, the BIG OPT approach may be applied to almost all types of processes, without using any software. Second, it is most suitable to use the SMALL OPT scheduler for the job shop environment, or very complex assembly lines. Third, OPT can be shown to be consistent with previously accepted MS/OR models. Thus the "mystery" of the OPT "black box" can be removed. The paper explains and analyses the OPT approach of classifying the various manufacturing processes into A, V or T types, and the OPT basic concept of drum–buffer–rope. Section 1 is this Introduction. Section 2 briefly describes the nature of MS/OR philosophy. Section 3 examines the main concepts of the OPT management approach. The discussion will be divided into six major parts:

(1) the goal, according to OPT;
(2) operational and financial performance measures according to OPT;

(3) OPT educational training;
(4) OPT techniques and concepts;
(5) the OPT rules; and
(6) the OPT software.

Then, the analysis divides those components into BIG OPT and SMALL OPT considerations. At the same time this section shows that any of the concepts can be related to known MS/OR concepts.

Section 4 describes an enhancement of the BIG OPT system, which is also known as the Theory of Constraints.*

Section 5 draws conclusions and suggests further research.

2. MS/OR PHILOSOPHY

The Management Science/Operations Research (MS/OR) philosophy is based on capturing the system's relevance in a model. The causal relations between one or more objectives (goals) and the factors that change the attainment of the objectives are usually represented by equations which include the mathematical functions that relate the independent and dependent variables [14].

MS/OR models are successful only if they include all of the independent variables that are relevant to the behavior of the dependent variables (objectives). Toward this end, a systems analysis which identifies all relevant causal variables is essential. Also, it is critical to explain the nature of the causal linkages that affect the system's performance. This includes the functional relationships between the variables (y is a function of x) and the existence of constraints (x must be greater or less than c). Although it further complicates matters, statistical variation must be included when it is relevant. Statistical modeling generally takes the form of expected values (averages) and, occasionally, measures of variance are introduced.

Because of complexity, optimization models are too often trite descriptions of a process that needs to be understood. Incorrect modeling can lead to serious suboptimization. In such cases, heuristic models are used to relate the objective functions with their causal factors. When MS/OR optimization models fail to capture the systems relevance (i.e. suboptimization), then practitioners seek to convert them to heuristic forms that will satisfy the need to improve the performance of real systems. This explains why BIG OPT is conceptually in tune with optimization models of MS/OR, and why SMALL OPT is associated with practical heuristic procedures.

Thus, the main issues highlighted by the MS/OR approach are:

- It is critical to have a clear definition of the system's objective functions: in this case, what really counts in financial and physical production output terms.
- A systems approach is needed to avoid missing factors and relationships that count in explaining the achievement of objectives.
- For realism, it is essential to model the system's variability (where it is sensitive to it) and constraints on its performance (when they occur).
- Where applicable, construct optimization models to indicate decisions that will lead to the achievement of goals.
- When optimization will not do the job, use the heuristic approach to by-pass suboptimization.

MS/OR models have been focussed on the same production management issues that concern OPT. Therefore, it is not surprising that OPT and MS/OR models converge as they attempt to describe similar kinds of phenomena. BIG OPT philosophy is congruent with the MS/OR objective to avoid misleading suboptimization. SMALL OPT scheduling algorithms which are consistent with this aim can be verified by MS/OR theories.

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*The methodology, developed by Goldratt as Theory of Constraints, will be referred to in this paper as Management by Constraints (MBC).

3. THE OPT PHILOSOPHY

The concepts of the OPT system can be divided into six major parts [1, 6]:

- The goal according to OPT.
- The operational and financial measures of performance of OPT.
- OPT educational training.
- The OPT rules.
- The OPT techniques and concepts.
- The OPT software.

We make a distinction between BIG OPT (the strategic and managerial OPT system) and SMALL OPT (the scheduler and its tactics).* The OPT goal, measures and concepts form the BIG OPT, while the OPT rules, techniques and software are part of SMALL OPT. As the analysis shows, one can use BIG OPT and the rules and techniques of SMALL OPT without purchasing the software developed by Creative Output Inc.

The goal

According to the OPT concepts, the goal is "to make money in the present as well as in the future" [1]. The OPT guidelines claim [2] that many organizations do not define their goals, and one of the main problems faced by management is contradictory goals for different divisions, plants and departments within the organization. The OPT goal can be viewed through mathematical programming as a "target function", or an "objective function". This fuzzy goal is used extensively by OPT, usually for eductional purposes. OPT translates it into operational goals through its measures, as seen below. OPT is an excellent example of a commercial product that uses a systems approach.

From the systems theory point of view, a system has a purpose and role, an environment, resources, components, people (users, designers, decision makers), and measures of performance [15]. A system has also input, output, and feedback.

It should be mentioned that the systems approach is, in our opinion, one of the most important concepts of the OPT system and one of the main key factors to its success. OPT is not sold as a "software package", or a "scheduler". OPT is a management system and, as such, it has inputs, outputs, users, measures of performance, components, and life cycles.

Operational and financial measurements

The OPT approach establishes three operational measurements, which are also parts of BIG OPT:

- Throughput;
- Inventory;
- Operating expense.

The operational measurements are well defined [1]:

Throughput is the rate by which an organization generates revenue through sales. According to OPT, if the system produces something which has not been sold, it is not considered throughput.
Inventory is defined as "all the money the system invests in purchasing things that it intends to sell". This definition of inventory deviates from traditional definitions since it excludes the added value of labor and overhead for work in process. This makes inventory measurement much clearer and enables management to watch the difference in WIP (Work in Process) and raw material without the overhead allocation noise.
Operating expense "all the money the system spends in order to turn inventory into throughput". This definition of operating expense includes not just direct labor, but also management overhead, computers, and so forth. This approach adds all production overhead [16] to the operating expenses.

*The same terminology may be applied to the Just-in-Time (JIT) concept. JIT may be divided into BIG JIT—the philosophy and strategic issues, and SMALL JIT—the tactics of scheduling using Kanban methods. While BIG JIT (containing JIT production philosophy, total quality control and total preventive maintenance) is usable in every process and industry, the SMALL JIT works best in repetitive processes only.

OPT philosophy suggests that by using the OPT principles, the three measures will be improved simultaneously: Throughput will be increased, Inventory reduced, and Operating expenses decreased.

OPT emphasizes its measures, and often criticizes many Western production systems for having inappropriate measures [2]. They preach against using "efficiencies" as measures of performance.

Dipping into the MS/OR literature, the OPT intention is epitomized by "use of measures that will avoid suboptimization". The "efficiencies" are local measures that cause suboptimization. This is the key to OPT measures.

There are also three financial performance measures in BIG OPT:

- Net profit;
- Return on investment;
- Cash flow.

OPT uses the traditional definitions for these commonly accepted financial performance measures [17]. OPT rejects "Cost Per Unit" as a productivity measurement, and emphasizes that the use of this measure yields larger lots, causing increasing inventory.

OPT argues with traditional costing systems that, in many cases, cause faulty "make or buy" and pricing decisions. Instead, OPT suggests designating two main types of resources: the scarce bottleneck resource and the non-bottleneck resource. According to OPT, indirect expenses (overhead/burden) should be allocated according to the use of bottlenecks. For further reading, the reader is referred to Eden and Ronen [18]. Traditional practitioners of cost accounting usually allocate overhead expenses by parameters such as direct labor hours, floor space etc.

OPT points out that cost accounting is "enemy one of productivity". However, it does not offer an alternative accounting system that is closed and complete.

OPT educational training

It should be noted that by using the systems approach, OPT pays much attention to *training and educating* the users long before any hardware reaches the plant.

After a feasibility study, all the managerial staff go through an extensive educational program. At this stage, the system's goals are explained and old, irrelevant concepts (i.e. "efficiencies") are openly examined in order to be abandoned. The education and training process begins with top management. Then, it goes downward to the rest of the employees. OPT invests substantial resources in the educational programs. OPT uses books, games and training programs [1, 2], video-tapes [19], microcomputer simulation games [5] and lectures. OPT has developed special courses, for various people in the organization, to make sure that all the participants (especially finance, accounting and marketing decision makers) will have a common language.

OPT techniques and concepts

SMALL OPT uses some common techniques and principles extensively:

The Pareto rule. It is well known that few inventory items usually account for most of the inventory value as measured by dollar usage. Thus, one can manage these few items intensively and control most of the inventory value. This principle, known as "the Pareto rule", or the 80/20 principle, is often used in many areas of business to classify the significant few items as "A Type" items. This classification analysis, widely known as the ABC Analysis, was developed by Del Harder of Ford in the 1940s. It is represented by the log-normal distribution.

It is used to determine bottlenecks, to explore candidates for setup improvement, and so on [20]. As noted above, OPT integrates this rule into its system with much success. The nature and behavior of the manufacturing environment does not allow accurate data because of the dynamic changes that occur regularly [21]. Thus, focusing on the main significant contributing items yields better decision making.

The Pareto rule, as used in OPT for gathering data and determining bottlenecks employs a completely different approach from MRP. OPT is based on the understanding that you cannot have, and you *do not need*, accurate data on everything all of the time. This is the reason that OPT focuses on the important data for the decision making process, and verifies only the important items.

As opposed to this approach, MRP uses an "accounting" type of system: all data are needed, and are treated equally regardless of their importance. No Pareto analysis is done, and no extra efforts are expended to verify critical information. OPT uses a systems approach, whereby the more important items are treated differently than the less important ones.

The effect of statistical fluctuations. One of the OPT principles is that in real life environments nothing is deterministic. There are statistical fluctuations in lead time, percentage of scrap, production time, and so forth. According to OPT, many scheduling and planning rules based on "averages" fail to be realistic and feasible, because statistical fluctuations must be treated for what they are, as they occur; not as they average out, over time.

The effect of dependent events. OPT points out that in the industrial production environment processes are dependent, and according to technological constraints one step can take place only after the completion of another. The combined effect of dependent events and statistical fluctuations yields less throughput and more WIP than the production scheduler normally anticipates [1].

Statistical fluctuations and dependent events are treated as a special case in the Production and Operations Management (P/OM) literature. The nature and understanding of statistical variation is one of the basic foundations of the management principles of W. E. Deming [22]. Deming's principles concerning variation are fundamental to understanding the OPT principle which implies that ignoring stochastic behavior is equivalent to ignoring the system.

The Deming approach for removing variability is not one of the OPT principles. OPT treats the system as it is and tries to make the best of the existing situation by better scheduling. Thus, OPT, as it is presently constituted, is not closed and complete. It does not strive to remove variability as done in Deming's works and in the JIT approach [23].

However, most production planning systems (e.g. MRP) treat the manufacturing environment in a deterministic way. OPT takes an approach similar to PERT while trying to find the bottlenecks (equivalent to the critical path in project management), and looks at the world from a stochastic point of view.

A main contribution of OPT is the recognition of the effect of statistical fluctuations and dependent events. This has not been done before, as far as we know, by a commercial production planning system, in a systematic way.

The effect of statistical fluctuations and dependent events is discussed widely in queuing theory. It is well known that design to achieve "high efficiency" in a stochastic environment may result in a large number of customers (WIP) in the system (e.g. any investigation of M/M/1 or M/M/S system will do). It should be noted that the OPT system implicitly assumes a stable system, so that at a given time we identify bottlenecks, have a stable order mix and given resources. This is not true for many unstable plants. We think that before implementing OPT, one should stabilize the system. This means "cleaning" the floor for unnecessary WIP, constructing a stable schedule, reducing lot sizes, and using other means to reduce the system's noise.

The concept of Drum–Buffer–Rope. Drum–Buffer–Rope (hereafter DBR) are the three components of the OPT scheduling and control system, and thus form an important part of SMALL OPT. The *drum* is the pace that dictates the production rate.

OPT makes a distinction between two types of constraints: bottlenecks and Capacity Constrained Resources (CCRs). A bottleneck is a resource whose capacity is less than or equal to the market demand. A CCR is a resource which, *if not scheduled properly*, can damage due date performance or throughput. Thus, depending upon available capacity, demand for service, and scheduling effectiveness, a resource can be classified in a two-dimensional table: i.e. being a bottleneck or a non-bottleneck; and being a CCR or a non-CCR.

Though OPT makes distinctions between a bottleneck and a CCR, for better initial understanding we may use both terms as synonyms. Moreover, since the differentiation between a bottleneck and a CCR is relatively new in OPT, all the OPT rules still refer to bottlenecks and non-bottlenecks only.

In some cases, where it is not feasible to schedule according to the bottleneck, or bottlenecks, or where there are no bottleneck resources in the system (e.g. the market serves as the system's binding constraint) the orders for the end-products act as a *drum*. Once the drum is established, no WIP is allowed in front of most of the non-bottleneck resources.

Special time *buffers* are planned in front of bottlenecks, to make sure that the critical resources do not stop working. *Buffers* are also allocated before assembly stations where products arriving from bottleneck resources are assembled. The buffer size is determined in terms of time. Their main purpose is to prevent the system from stopping because of statistical fluctuations. Another place where buffers are located is in front of the orders. This enables the user to control the due dates and supply.

The *rope* is the third component in the OPT scheduling concept. Since scheduling is done according to the drum. The rope is the offset of time between the scheduling of the *drum* and the release of raw materials.

Figure 1 demonstrates the DBR approach. Machine 2 is the bottleneck and, for this example, its production rate serves as the *drum*. It dictates the pace for the whole system. To avoid disruptions, a buffer is built in front of the bottleneck. OPT uses a "rule of the thumb" and determines the time buffer size to be 1/4 of the total current actual lead time.

The DBR approach to scheduling makes a major contribution to the field. In traditional MRP systems the orders serve as the "drum" all the time. Backward scheduling is done from the orders to the subassemblies and raw materials. The OPT concept suggests that the drum can be either at the end of the process, or at any other place. The drum is identified according to the circumstances, and in cases where the market demand exceeds the process capacity, it is the bottleneck of the system. Thus OPT is more flexible than MRP. In many cases MRP puts the drum in the wrong place.

Figure 2 shows the OPT approach as opposed to MRP in placing the drum. The time buffer concept is not a new concept in the MS/OR literature. This idea has been used in MRP systems and in other theoretical studies. The concept of having inventory as an "insurance policy" on the time axis is not unique to OPT. The OPT contribution at this point is to assign time buffers in front of bottlenecks and in other critical places (in front of the orders and in front of assembly points). However, further research is needed to determine the optimal time buffer for OPT users,

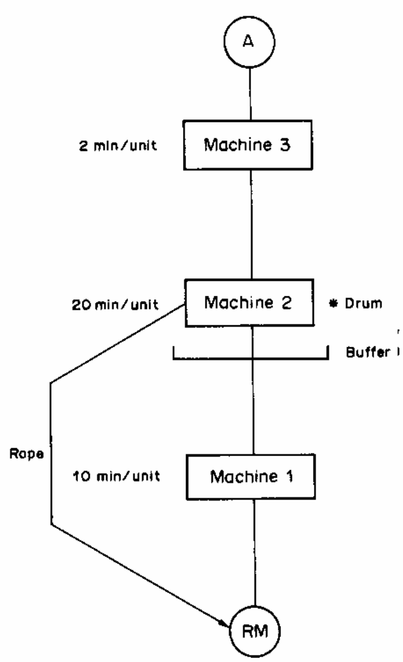


Fig. 1. The drum–buffer–rope.

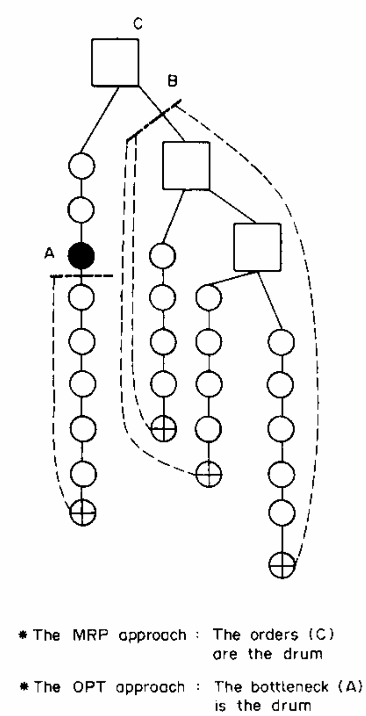


Fig. 2. Placing the drum: the MRP approach vs the OPT approach.

rather than employing the heuristics suggested by OPT. In MRP systems, time buffers are assigned through extended lead times for *all* the activities. One may use the MRP system and use the DBR approach at the same time: he would use the orders as the drum, assign zero lead time to all the activities, except for the bottleneck resource.

Is DBR a "push" or a "pull" system? Mainly it is a combination of both. Raw materials flow to the gate in a "logically controlled pull" way via the rope. Once they reach the floor they are pushed on.

The classification of V, A, and T processes. Unlike traditional classification of processes as continuous flow shops, assembly/repetitive lines, and job shops, OPT classifies all processes to be one of the following three: V process, A process or T process. Thus plants are categorized by the type of process flow [24].

A V process has a V-shaped process flow. It has a singular raw material (or minimal number) and a wide variety of unique end items. There exists parallel routing with common machining activities and a process flow orientation. V plants can be found in process flow industries, i.e. in paper mills, petroleum refining, and so on.

An A plant or an A process has an A-shaped process. There are numerous raw materials, and a limited variety of unique end items. Parts follow different routings and do not necessarily use the same resources. Feeder plants and assembly lines are examples of this type of process.

A T plant is characterized by numerous combinations of end items obtained from a limited number of component or subassembly parts. Final assembly scheduling is based upon actual customer orders. Car manufacturing is typical of this type of process.

Once a plant has been characterized to be a V, A or T plant, different methods are applied for the identification of bottlenecks and the assignments of time buffers.

The VAT classification has early origins: Starr, calling upon earlier work, divides production lines into *synthetic* and *analytic* processes [25, p. 182]. Synthetic means that many inputs combine to form a lesser number of outputs, which is what OPT calls an A process. Analytic process means that few inputs are treated to produce a greater number of outputs. This is the OPT V plant. Schroeder notes that users of MRP systems can be classified by the type of bill of materials (BOM) they have [26, p. 447]. He divides systems into Process industry (a V plant), Assembly industry (a degenerated A plant) and Assembly and Fabrication system (a "classical" A plant). APICS [27, p. 15] has formulated the same VAT classification, under different names (see also McLeavy and Narasimhan [28]).

The OPT contribution to this area is 2-fold: first, the terminology is easy to use and enables communication between people at all organizational levels, and facilitates good communication and clear definitions; second, and especially important, is the use that OPT makes of this VAT classification scheme. The taxonomy was not applied for this purpose before. OPT took a step ahead and *used* this classification for practical purposes, namely: identification of bottlenecks/CCRs are done in different ways in each of the three environments. Different implementation techniques are carried out in the various plant/processes.

The nine OPT rules

In addition to the goal and the operational and financial measures of performance for BIG OPT, the procedures for scheduling throughput and for managing inventory are based on nine rules. The nine OPT rules are considered part of SMALL OPT. Scheduling oeprations by SMALL OPT can be done using the OPT rules and the OPT techniques, with or without the OPT software.

We will now show the nine OPT rules viewed as special cases of mathematical programming and other methods:

(1) Balance flow, not capacity. It is often counter-productive to attempt to balance capacity in order to get a flow-balanced plant. Instead, the idea of balancing the flow of existing systems was adopted by the Just-in-Time Japanese methods in the 1970s. This concept is in many cases supported by "pull systems". In a pull system, the (downstream) stage "pulls" parts from preceding stages, as needed, through successive stages of manufacturing. The pull system matches production with needs [29]. Every "pull" system balances the flow automatically, and thus the first rule of OPT is used by everybody employing the SMALL JIT methods. The Japanese efforts to reduce setup times (see, for example, Shigeo Shingo [30]) is aimed toward a flow-balanced plant.

There are some differences between the Japanese methods and the OPT system to balance the flow. The Japanese use physical "ropes" (Kanban) while OPT uses logical release of raw materials. The methods used to reduce setup times to balance the flow are also different. While the Japanese use "trial and error" methods that take a long time (more than a year—see Schonberger [31]), the OPT system uses the DBR heuristic technique to cope more rapidly with this problem.

It may be noted that OPT and JIT do not compete in the same market. The SMALL JIT techniques and philosophy are more appropriate to assembly and repetitive industries where balancing a line might take time and the process is flow through. SMALL OPT is best suited to a job shop environment, where "trial and error" will not lead anywhere, because situations are constantly shifting. In this complex environment, the use of some heuristics to quickly balance the flow is critical.

We observe that the MRP-based systems tried to cope with the capacity-balance problem through the MRP II systems. It has never been the strong part of MRP to balance either the capacity or the flow. MRP is often used in the job shop environment but assumes a continuous flow system, thus ignoring and missing bottlenecks that cause the poor performance of MRP.

(2) Constraints determine non-bottleneck utilization. One of the main OPT principles is to distinguish between a bottleneck and a non-bottleneck resource (and CCRs and non-CCRs). According to OPT, in the plant there are only a few CCRs, and thus it is easier to control them. All of the other resources' utilization is determined by the bottleneck resources.

The idea of bottleneck and non-bottleneck resources can be viewed as a special case of mathematical programming. For exmaple, in the Linear Programming (LP) area, a scarce resource can be viewed as a bottleneck and the non-scarce resource is the non-bottleneck.

To illustrate this point, let us take an example, given in The Race [1] for managers' education and training.

The example we are going to analyze is shown in Fig. 3.

We will solve this problem using LP techniques, to demonstrate the equivalency to the bottleneck and non-bottleneck techniques.

Let x and y be the number of units of products B and C respectively, to be produced per day.

The target function is:

$$\text{MAX } (x + y)$$

The constraints follow:

1. the demand for C: $x \leqslant 200$;
2. the demand for B: $y \leqslant 100$;
3. worker V constraint $y/60 + x(1/60 + 1/60 + 4/60 + 2/60) \leqslant 24$ or $y/60 + 8x/60 \leqslant 24$;
4. Worker W constraint $10x/60 \leqslant 24$ or $x/60 \leqslant 24$;
5. $x, y \geqslant 0$.

Using the Simplex algorithm, the optimal solution is $x = 144$ and $y = 100$, which is the same solution given by OPT. Referring to Fig. 3, the detailed solution can be derived as follows:

Worker V will produce the following quantities:

the C-10 part: 144 units;
the B-10 part: 244 units;
the A-30 part: 144 units;
the A-10 part: 144 units.

Worker W will produce 144 units of the A-20 part.

Specific scheduling will follow this solution and get the same results as OPTs: worker W is the scarce resource (the bottleneck) and should be working all the time. Worker V can be scheduled accordingly.

The LP solution indicates that worker W is a scarce resource, as the OPT solution indicates that worker W is a bottleneck.

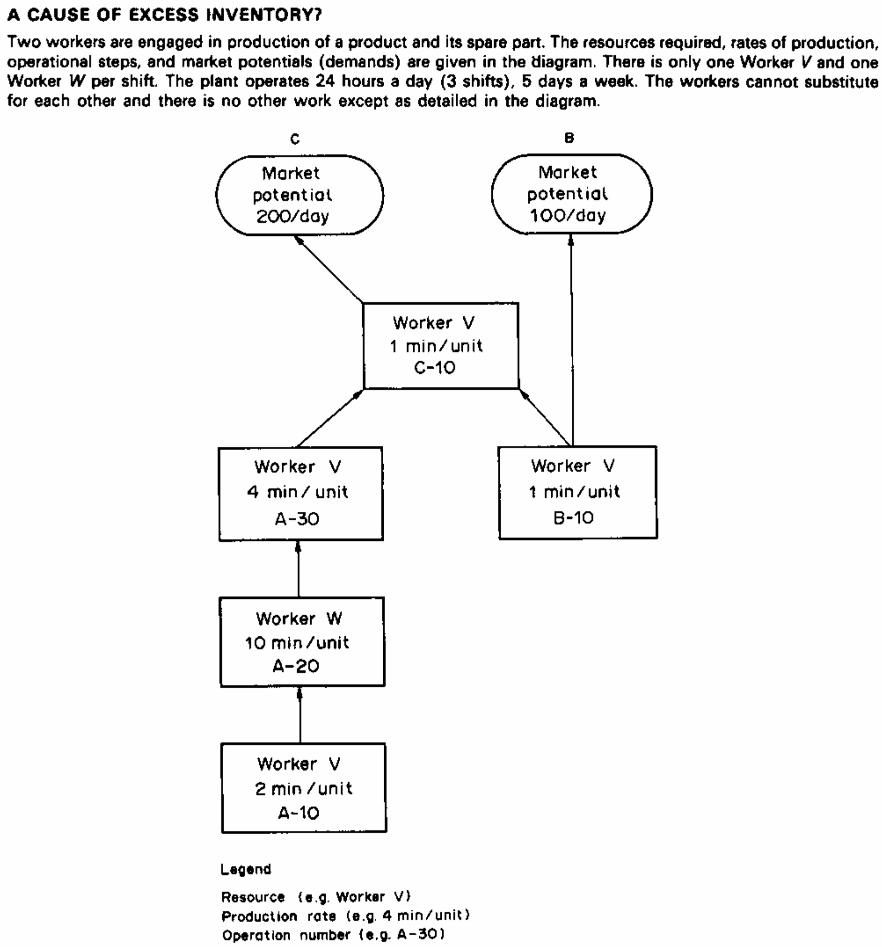


Fig. 3. OPT: Case 1.

From the OPT solution, as well as from the LP solution, we can see that non-bottleneck (non-scarce) resources are utilized by the constraints (the bottleneck-scarce resources). Thus the concept of bottleneck and non-bottleneck resources can also be viewed directly as mathematical programming constraints.

(3) Activation is not always equal to utilization. As noted by [6], the meaning of this rule is that "to activate a resource when the resulting output cannot get through a bottleneck is wasteful in the form of excessive inventory". LP can explain the phenomenon by using the shadow prices of resources. The shadow price of a non-scarce resource is always zero. Thus, activating a non-bottleneck resource more than the determined utilization level does not add any value to the target function.

(4) An hour lost at a bottleneck is an hour lost for the entire system. According to OPT, if we have a bottleneck "that is utilized to its full potential, an hour lost at that bottleneck can never be made up. Output of the entire factory is lost" [6].

This can be explained by the mathematical programming approach: a bottleneck is a scarce resource, and as such it has a positive shadow price. Decreasing the amount of this resource will decrease the target function (in this case, maximum throughput) accordingly.

(5) An hour saved at a non-bottleneck is a mirage. By definition, a non-bottleneck resource is made up of three time elements: run time, setup time, and idle time. Since a non-bottleneck resource is not used 100% of the time, saving time at that resource will only increase the idle time, and therefore is a mirage, in OPT terms.

Taking into consideration the LP approach, a non-bottleneck is a non-scarce resource which has a zero shadow price. Thus an hour saved there may be viewed as a mirage.

This assumes a stable environment. However, in a variable environment a non-bottleneck can become a bottleneck and destroy the mirage. It is very common in the job shop environment that bottlenecks wander from one resource to the other, and saving in non-bottlenecks can save operating expenses in the long run and provide more flexibility in the short run. As we see it, one should begin saving time in bottleneck resources and then keep improving the non-bottleneck ones. For example, saving setup time can be done on bottlenecks first. Karmarkar [32] and Karmarkar, Kekre and Kekre [33] use queuing models to emphasize that because of the variability in the manufacturing environment, every resource is a potential bottleneck. The "degree" of bottleneck varies depending on the expected utilization. Their model provides guidelines for setting process batches at different work centers.

It would be interesting to compare the Japanese approach to reduce setup everywhere with the OPT one of saving time only on bottlenecks. The Japanese approach is to reduce setup time at all stations. This is sensible because most of the JIT techniques are utilized in repetitive assembly lines where many resources can be considered bottlenecks. The lines have been synchronized in such a way that production will flow continuously. Thus most of the resources are close to bottlenecks.

(6) Bottlenecks govern throughput and inventory. This results from the former OPT rules. A scarce resource is the resource that governs the other resources and thus the output of the system. Part of the OPT philosophy lies in this rule. Traditional MRP II systems operate in such a way that *orders* govern inventory and throughput. In other words, the orders are the MRP II *drum*. In other cases, organizations initiating order fulfilment through acquisition or stocking of raw materials use *raw material* as the *drum*. The drum is the facility or machine that governs throughput and inventory. If you do not let the drum govern—there is no synchronization.

The OPT approach is that the *drum* can be anywhere in the process, not only at the end (as in the MRP case) or at the beginning (the raw material case). It can be a bottleneck that exists somewhere at the middle of the process that serves as a drum, and thus governs throughput and inventory. The contribution of the OPT approach in this case is 2-fold: first it is the scarce resource that governs the system and acts as a drum; and second, this drum can be anywhere in the process.

It should be noted that bottlenecks cannot govern throughput and inventory all the time. In some complex cases (e.g. elaborate T plants and job shops) where scarce resources are either difficult to identify or constantly changing in a dynamic environment, this rule of OPT is not feasible to apply. There may also be several bottlenecks at the same time. In these cases, it is suggested to take the orders as the drum. In many other cases, where there are no bottleneck resources, the orders (i.e. the market demand) serve as the drum. Once again we see the OPT assumption that there exists an internal production constraint.

(7) Transfer batch should not always equal a process batch. This means that one can produce a process batch and transfer it to the next station in partial lots, called transfer batches. This was done by JIT long ago, where the race was to achieve a one unit processing batch and one unit transfer batch. The concept of changing a transfer batch from a process batch is related to the process and assembly lines, where the process lot can be considered infinite, and the transfer lot is one.

To illustrate this, OPT has solve Quiz number 2 in Goldratt and Fox [1].

Figure 4 shows the problem and Fig. 5 shows the proposed OPT solution. The OPT solution suggests a 50% setup of the non-bottleneck resource (worker W).

We may suggest a better solution, taking into consideration that the transfer lot should not always equal the process lot. We suggest a transfer batch of 1, and thus the solution for this problem will be as follows:

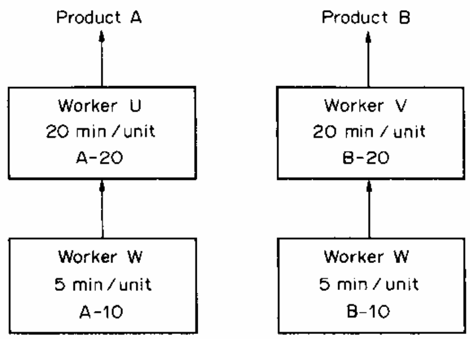
Let y be the production lot size and let 1 be the transfer batch size. Let us assume that worker U is working now, and count the time needed for worker W to complete a full cycle. The setup time on A is 3 hr—based on worker W.

The production lot on A is $y * 5/60$ hr. The setup on B is 3 hr—based on worker W. It takes 5/60 hr to produce the first part. During that time, worker U has finished a lot of y units, at

HOW FREQUENTLY SHOULD YOU SET-UP?

The market potential (demand) for Product A and Product B exceeds the plant's capacity. There is only one Worker *U*, one Worker *V*, and one Worker *W* per shift. The plant operates 24 hours a day (3 shifts), 5 days a week. The workers cannot substitute for each other and there is no other work, except as detailed in the diagram specifying the required resources (type of worker), rates of production, and sequence of operations.

A set-up of 180 min is required of Worker *W* to start production and whenever he switches from one product to another. You may assume that no scrap occurs in this setup.



Legend

Resource (e.g. Worker U)
Production rate (e.g. 20 min/unit)
Operation number (e.g. A-20)

Fig. 4. OPT: Case 2.

$y * 20/60$ hours. Thus,

$$3 + y*5/60 + 3 + 5/60 = y*20/60$$

$$6 + 5/60 = y/4$$

$$y = 24.333$$

This solution uses an approach similar to the OPT method of solution, with no less effective results.

The lack of normative models to solve the general case of the process lot and the transfer lot under different conditions calls for further research.

(8) Process batches should be variable, not fixed. This rule can be derived from mathematical programming concepts: once we change the work rate or output coefficients or the target function, the batch sizes are going to be changed accordingly.

(9) Set the schedule by examining all the constraints simultaneously. This is exactly what is done by LP (as shown in the equations above). Setting all the constraints simultaneously allows us to avoid suboptimization as well. (On the other hand, if some constraints have zero shadow prices,

HOW FREQUENTLY SHOULD YOU SET-UP?

The usual way of setting the frequency of setups is to minimize the cost/unit (the sum of the setup cost plus the carrying cost). Many articles have been published dealing with this problem, under the title "Economic Batch Quantity". In most places a rule of thumb is used, setting the production time to be larger than the setup time by some factor (usually between 4 to 10 times).

The OPT approach starts by identifying the constraints of the system. In our case, *U* and *V* are clearly the constraints since each one of them requires 20 min/unit-pair, while *W* requires only 10 min/unit-pair (5 + 5). Thus *W* can be productively utilized for producing parts only 50% of its time. Any production beyond that will just yield inventory but not additional sales. Since 50% of *W*'s time is free, why not utilize it for setup, thus reducing inventory without any reduction of sales?

Since the setup time at Worker *W* is 3 hours, the batch size at each of its operations should also be 3 hours, or 36 parts (3 × 60/5). However, we should avoid full utilization of *W* to prevent any fluctuation of *W*, *V* or *U* from causing lost sales. Therefore, the most efficient batch size would be a little larger than 36. This will result in sufficient idle time and inventory to cushion fluctuations.

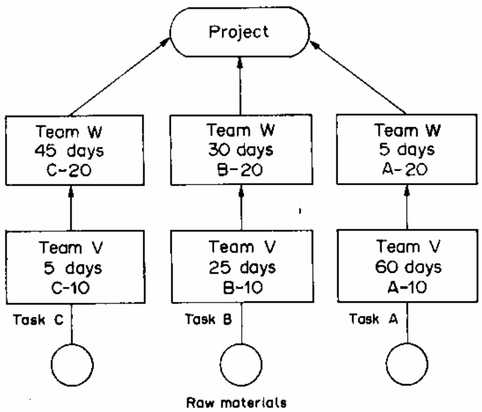
The conventional attempts to save setups on non-bottlenecks do not really save anything. They simply increase the amount of unneeded spare time. This is a demonstration of Rule 5 of OPT:

"AN HOUR SAVED AT A NON-BOTTLENECK IS JUST A MIRAGE"

Fig. 5. The OPT solution for Case 2.

SHOULD CPM/PERT BE USED FOR PROJECT PLANNING?

The project has to be completed in 150 working days from today. To complete the project, all 3 tasks (A, B, C) have to be completed. The diagram specifies the resources (teams), operation times, and the sequence of operations for the project. There is only one Team *V* and one Team *W* available for the project. The lead time for procurement of the materials needed (described in the diagram as circles) is 50 working days for each material.

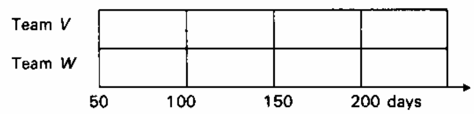


Legend
Resource (e.g. Team W)
Operation time (e.g. 45 days)
Operation number (e.g. A-20)

• Use CRITICAL PATH or PERT to determine when to order each material.

Materials for Task	Day to Order (in working days from start)
A	
B	
C	

• Draw the schedule for the project (Gantt Chart).



• Will you finish the project on time?

• Try again—using your intuition this time. When is the earliest possible time you can finish the project?

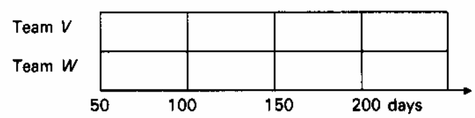


Fig. 6

they are not to be considered simultaneously. Thus, this OPT rule does not tend to be true for all cases.) These are the binding constraints that we are interested in.

Case 5 in Goldratt and Fox [1] illustrates this rule of OPT. Figure 6 depicts this example.

We know that Johnson's Rule* is a simple rule which yields a minimum processing time for sequencing *n* jobs through two machines or work centers. It requires that all jobs be listed and the amount of time each requires on a machine be shown. The jobs are then scanned for the shortest individual activity time. If the shortest time lies with machine A (the first one), then the job is placed as early in the schedule as possible. If the shortest time is on B, place it as late as possible. Once the job has been scheduled, it is eliminated from further consideration, and the decision rule is applied to the remaining jobs.

Using Johnson's Rule we obtain the same schedule.

The OPT software

Not much has been published on the OPT software. The lack of publication created a mystery and the inference of a "secret algorithm". This added to the confusion in evaluating OPT. Since OPT charges hundreds of thousands of dollars for the software, only large companies with high-revenue production lines can afford to buy the software.

Even if one does not buy OPT software, we can still answer the question: how does the SMALL OPT software work? It is fairly well understood that the OPT procedure of scheduling tasks is as follows:

First, building and maintaining the data required for OPT to model the plan is the most time consuming and difficult task in its operation [7]. The bill of materials, routing sheets, market requirements, inventories, and work center data (setup times and processing times) are combined into a consolidated network for each end product.

The OPT software module BUILDNET is used to link that data together and also to check for errors as it processes. Then, a procedure called the OPT SERVE module provides a load profile for each of the resources and calculates average utilization of each resource.

*Heuristic developed by S. M. Johnson [34].

Next, a resource load analysis is performed using the Pareto rule to determine bottlenecks. Because of inaccurate data, the most loaded resources are checked manually. According to OPT, fewer than 5% of the machines are usually considered to be bottlenecks.

At this point, a module called SPLIT is used to divide the network into two areas: critical and non-critical resources. The scheduling procedure takes place using the OPT module for the bottlenecks. The OPT module contains the undisclosed algorithms developed by Creative Output Inc.

The Capacity Constrained Resources (CCRs) dictate the schedule based on market demand and their own potential. Since the two major constraints on the plant are the market demands (the amount of product we can sell) and the capacity of the CCRs, it will make sense to base our schedule on these two constraints.

Thus the first step will be to determine the schedule of the CCRs by taking into account only their limited capacity to fulfill the market demands that they are trying to satisfy. Once the CCRs' schedule is established, we need to determine how to utilize all the non-constraining resources. Using the schedule of the CCRs, the utilization of the succeeding operations can be derived. Once the part is completed at the CCRs, it is scheduled at the next operation.

While the CCRs' scheduling, transfer and process lot sizes are determined by the OPT module, SERVE determines the non-critical resources.

Now OPT must schedule the prior operations to protect the CCRs from disturbances that might occur at the preceding resources. Thus, a time buffer stock is built up, and all the preceding operations will be back-scheduled.

In this way OPT generates a schedule and a time buffer that will satisfy all the requirements. We note that so far time buffers are assigned only before a CCR. In order to assure meeting customer due dates, the assembly schedule is dictated by the availability of scarce parts coming from the CCRs. Any assembly using the output of a CCR (directly or indirectly) must have a time buffer on other branches of the product structure to insure against disruptions that might occur in procurement and manufacture of the other parts.

Following this approach, the scheduling of parts should be derived backwards in time, starting now, utilizing the time buffer in front of assembly. Thus, OPT is using forward scheduling for operations (including assembly) succeeding the identification of the CCRs.

The schedule of preceding operations should support the time buffer and thus be derived backwards in time from the CCRs' schedule. If non-critical resources scheduled by SERVE show over 100% utilization, then errors in data are again checked and corrected, or the resource is moved to the critical portion of the network and a second iteration is performed. These iterations are repeated until a schedule is produced without any resource utilized over 100%.

4. MANAGEMENT BY CONSTRAINTS—AN ENHANCEMENT OF THE OPT SYSTEM

Late in 1986 some of the Creative Output founders left the company and concentrated on the education and training area [18]. The methodology, known as Management by Constraints, is verbalized as follows:

Set up the system's goal and use the right measures.
Then, follow the next five steps:

(1) Identify the system constraint(s).
(2) Decide how to exploit the system constraint(s).
(3) Subordinate everything else to the above decision.
(4) Elevate the system constraint(s).
(5) If, in the previous steps, the constraint has been violated, go back to step 1, but do not let inertia become the system constraint.

The OPT rules, as well as the DBR approach, can be viewed as special cases of the five steps of MBC. The DBR concept identifies constraints: an internal one (bottleneck) or an external one (market demand). The chosen constraint is the drum. Once it is identified, we decide how to exploit it (e.g. let the bottleneck work 100% of the time, build a buffer in front of the scarce resource to protect it, etc.). We subordinate the whole system to this decision. The release of raw material and the utilization of the non-constraint resources are determined according to the drum pace.

Employing the 5 steps, the rules of OPT fit the MBC methodology in a useful way. One may view it as a clear application of linear (or mathematical) programming. We first set the target function, and then the LP (for instance) gets us to the solution. We identify the constraint (having a positive shadow price), and the rest of the decision variables are automatically subordinated to it. We elevate the constraint by buying more units of the same, until the constraint is broken.

MBC is the broad way to express BIG OPT concepts, and it is definitely an advanced step beyond what is normally considered OPT. Reports on successes of the GOAL implementations, as well as successful implementations of MBC, tend to prove the idea that it is not the software that makes the significant contribution.

5. CONCLUSIONS

Synchronized manufacturing as in OPT is a new concept in production management which has spread rapidly in industry. OPT concepts can be viewed as an integration of key notions that lead to effective applications. OPT uses the systems approach to decrease suboptimization and to obtain measures of performance that fulfill the system's goal.

OPT makes a definite distinction between a scarce resource (bottleneck, or CCR) and a non-scarce resource (non-bottleneck). The OPT approach encourages using small lots and differentiates between transfer lots and production lots.

The main contribution of synchronized manufacturing by OPT may be explained by the following:

(1) BIG OPT uses the systems approach, emphasizing education and an extensive training program, and utilizing different measures of performance and definite goals. OPT recognizes that the main problem does not lie in software or hardware solutions, but in changing management attitudes. Productivity can and should be improved first by avoiding the use of traditional cost accounting measures for production decisions.

(2) BIG OPTs target of reducing cycle times is, in our opinion, the main OPT strategic operational goal. This is done by reducing inventories, exploiting bottlenecks, and careful release of raw materials using the DBR approach.

(3) The DBR concept enables OPT to schedule complex operations in a flexible way. As opposed to MRP, OPT can allocate the drum anywhere, while the MRP approach enables only orders to serve as the drum.

(4) The use of the VAT classification provides management with a simple but powerful tool to analyze the production environment and identify bottlenecks.

(5) OPT is a stochastic production concept. Unlike the deterministic approach of MRP, OPT is based on the phenomena of statistical fluctuations and dependent events. Thus, schedules that use the OPT concepts are more realistic than those of MRP.

To the best of our knowledge, the first three points, namely the BIG OPT components, constitute the major reason for OPT's success. That means that without buying the OPT software, one can improve productivity. This in turn opens a niche for system's oriented entrepreneurs to develop alternative heuristics (or alternative "SMALL OPTs"). In our opinion, creating an inexpensive personal computer-based scheduler using the BIG OPT concepts may be a real breakthrough for many small and medium size firms. This PC based software may also act as a Decision Support System [35].

OPT has done an important job in translating terms used by professionals into day-to-day language. For example, not many people use terms such as "scarce resources" and "non-scarce" ones. Yet, we hear today more practitioners talking about "bottlenecks" and "non-bottlenecks". "Target function" and "objective function" are used by an increasing number of people outside academia. The "goal" is widely employed by many managers.

A substantial contribution of OPT was to be one of the first systems to question accounting measures ("efficiencies") that damaged industry performance.

In this paper we showed that the OPT concepts may be viewed as based on known MS/OR principles. It is an integration of those concepts. The problem of the "black box" approach (the proprietary computer software package) inhibited use of the OPT system. This problem can be bypassed either by uncovering the software package or by developing alternative software packages by independent suppliers.

Where would OPT work best? In this paper we made a distinction between BIG OPT and SMALL OPT. BIG OPT is suitable for all types of manufacturing. The principles of system management, using good performance measurement can be used in all types of processes and industries, service and goods production. The way OPT implements its systems can serve as a model for implementation. We find the SMALL OPT to be most suitable for the job shop environment or complex assembly lines. This logical conclusion calls for an empirical study to explore the issues.

Who needs the OPT software? BIG OPT and SMALL OPT can work in most cases without the OPT software. To the best of our knowledge, most of the benefits obtained by OPT are gained by using BIG OPT and SMALL OPT concepts and techniques. In large job shops, or complex assembly lines, one may need the OPT software, only after gaining all the benefits working according to BIG and SMALL OPT concepts and techniques. This also calls for further research.

Can OPT work together with MRP systems?

As we view industry, most MRP II users make much of the package by using it as a data base (BOM, inventory, purchasing, routing files and so forth). Very little is done today in using MRP as a shop floor scheduler. BIG OPT can be used together with MRP II software, where the scheduling will be using SMALL OPT concepts. The suggested personal computer software mentioned above can use the MRP data base. This seems to be a good solution for most shop floors. It is also expected that the micro SMALL OPT scheduler would use artificial intelligence concepts and techniques, using LISP based machines. Also, with trends to set up manufacturing cells and simplify the production process, already researchers have tested PC based software, CLASS [36], that seems to perform well. Thus, OPT deserves the credit for creating interest in this field.

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