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Applications of Implosion in Manufacturing Planning

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IBM Production Resource Manager offers implosion-based software solutions for computing optimal production schedules

Materials Requirements Planning determines the total number of components required by a manufacturer in a given timeframe. The main calculation step -- multiplying the total number of each component required per finished piece by the total number of finished pieces to be produced -- is the basis for the "explosion" method.

The "implosion" method, on the other hand, allows a manufacturer to calculate -- from the total number of each individual component available -- the number of finished pieces that can be produced.

IBM Production Resource Manager is a software tool that enables a manufacturer to use the implosion method in conjunction with its Materials Requirements Planning system to calculate optimal production schedules.

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Manufacturing firms compete on the basis of cost, quality, and delivery. They are under constant pressure to deliver better quality products more quickly at lower cost. Manufacturing companies use a variety of software tools to improve the quality and speed with which decisions are made. In this paper we briefly discuss MRP/MRP II environments, and describe limitations of some current practices, including a situation within IBM which led us to develop new models and software tools for manufacturing resource allocation. Two specific applications that we have built are described. The underlying mathematics and the solution methods are also discussed.

Current Practice:

A common activity in many manufacturing firms is material requirement planning (MRP). The primary input data to MRP, the *master production schedule (MPS)*, is defined as “the anticipated build schedule for those items assigned to the master scheduler”. The definition further requires that the MPS take into account "backlog, availability of material, availability of capacity, management policy, and goals," and resolve competing demands for limited resources. The MPS has often been identified as a critical but poorly addressed issue in manufacturing planning. Burcher's survey (1991) indicates that relatively few companies are attempting resource requirements planning, rough cut capacity planning, and capacity requirements planning, and that very few companies were executing these processes successfully.

The lack of success in resource and requirements planning can be partially attributed to the absence of "bottom-up re-planning" support in MRP II. In APICS, "bottom-up re-planning" is defined as "... the process of using pegging data to solve material availability problems. This process is accomplished by the planner (not the computer system), who evaluates the effects of possible solutions." Re-planning becomes necessary as a result of development delay, engineering changes, order cancellations, previous scheduling errors, part shortages, or quality problems. Lee and Billington (1991) state that Hewlett-Packard Company managers report "incoming part availability and part delivery performance are the most important problems they face today." Several data analysis tools are available to aid in the re-planning process. These tools identify each plan inconsistency (e.g., shortage), and peg the requirements for a scarce resource to the higher level assemblies that use it. The planner must then resolve inconsistencies, one at a time, usually without consideration of the interdependencies implied by the BOMs. Pegging can be helpful, but it does not provide a means for globally assessing shortages. Some software companies have developed MRP emulators, which can regenerate a material requirements plan in minutes on high-performance workstations. These "decision-servers" (Shepherd, 1993) act as a front-end to the MRP II system, provide the planner with graphical applications for interactive simulation of material planning, capacity planning, and master scheduling, and allow the planner to evaluate the quality of alternative plans. These tools are not truly "schedulers" because they are only capable of evaluating a proposed schedule. They cannot *generate* a feasible MPS, let alone determine a schedule that is both feasible and optimal with respect to economic factors.

Capacity planning, master production scheduling, production scheduling, and final assembly scheduling all specify an allocation over time of the available material and capacity resources to competing production activities. Material resources includes both parts that are purchased from other firms and subassemblies that are produced internally. Capacity resources include manufacturing machines, tools, and operators. The distinguishing factor between these two types of resources is that unused material remains available for later use, while unused capacity (e.g, machine idle time) does not. In the electronics industry, world-wide shortages of certain key components that are used in many different products are not uncommon. Deciding how to divide the limited quantity of these scarce resources among the different products that require them is equivalent to deciding which products to make and which customers to serve. In other industries, where long-term world-wide shortages of raw materials are less common, long component lead-times together with variability in demand can require deciding not which products to make, but rather which products to make *on time,* and which products to ship late.

IBM Experience:

In the late 1980's the PS/2 card plant in Austin experienced shortages of key electronic components that were used in the production of several different PS/2 cards. IBM's world-wide material planning process required the card plant to commit an availability schedule for PS/2 cards within a few days of receiving card requirements and component availability information. The card volume planners had no tools, other than simple spreadsheets, to aid them in allocating the scarce components to cards. The Enterprise Shortfall Implosion Tool (ESIT), which provided allocation capability was implemented for Austin in 1990 (Dietrich and Escudero 1990). The term "implosion" was used to convey the idea that this tool provided "bottom-up" planning, rather than the traditional "top-down" explosion-based planning used in MRP. Since 1990, the implosion model used in ESIT has been extended to accommodate very general manufacturing models, including multi-level BOMs, capacity limits, multiple sources of demand, substitute parts and capacities, and a variety of allocation criteria. The entire software system has been re-designed to use object technology on the RS/6000 workstation. This new generation of implosion technology includes a very flexible application programming interface (API) which permits rapid development of customized applications. Implosion applications, ranging from final assembly scheduling to world-wide allocation of scare components, are being deployed throughout IBM manufacturing.

The difference between implosion-based planning and traditional MRP and CRP can be understood in terms of the inputs, assumptions, and outputs of these two methods. Both MRP and CRP consider the top-level demand (MPS) to be fixed input data and assume infinite material and capacity availability. MRP calculates required supply quantities and CRP calculates required capacity levels, and both generate recommendations for changes to purchase orders. In contrast, implosion takes the material and capacity availability to be known, *finite* input data, and treats the top-level demand as a desirable but not necessarily attainable target. Implosion calculates modifications to the MPS that ensure feasibility and optimize specific economic criteria. In addition, implosion models can be extended to consider factors that cannot be represented with traditional MRP/CRP methods, such as allocation of production to customers or demand classes, use of substitute material, and allocation of production to alternative capacity sources.

Implosion Applications:
The *Constrained Material Requirements Planning* (CMRP) application is used by procurement planners when the availability of either manufacturing capacity or some purchased materials is constrained. Standard MRP logic does not explicitly consider capacity or the availability of parts from suppliers. As a result, it can generate purchase orders that exceed known availability limits. Furthermore, if the materials that are readily available are purchased without regard to the availability of the short materials, then large inventories of unusable parts can be created. By producing an MPS that respects capacity and material availability limits, the purchase orders for unconstrained materials can be generated so that those materials arrive just-in-time for use. The application can also be used to manage material that is available, but subject to long procurement lead times.

CMRP quickly calculates an MPS that accounts for availability of constrained materials, procurement lead-times of unconstrained materials, manufacturing capacity, and demand. It also determines a shipment schedule for the demands, a production plan for all products, requirements for unconstrained materials that support the production plan. It then identifies the most critical resources and analyzes the benefit of increasing resource availability. CMRP can use either demand priorities or economic factors to drive the resource allocation decisions.

CMRP also computes the unused quantity available of each material and the utilization of each capacity. These schedules can be viewed with CMRP's graphical user interface (GUI), and the user can perform "what-if" analysis by adjusting input data and re-running CMRP's computations. CMRP's allocation logic can be applied to either long-term planning problems (e.g., how to deal with a world-wide shortage) or short-term execution problems (what to build and purchase this week).

The *Constrained Available to Promise* (CATP) application provides customer order management support. In production environments where common resources such as material, labor, and machine capacity, are used in various combinations to produce a variety of end items, it can be difficult to determine the earliest possibly delivery date for a given item. Common methods of quoting customer delivery dates, such as manufacturing lead-times or MPS netting, can result in either overly conservative or unachievable delivery date quotes, particularly if the MPS does not account for capacity and material availability. CATP quickly calculates reliable "product availability" schedules that account for current customer orders, material availability (on-hand and committed on-order), manufacturing capacity (machine, manpower), and forecasted demand. CATP can be used to determine appropriate responses to changes in order backlog, demand forecast, material availability, and manufacturing capacity. In addition, CATP can be used to determining the earliest possible date that an unforecasted order (e.g., new customer or special bid) can be completed.

Since customer satisfaction will suffer if committed shipments are delayed, CATP first allocates the available resources to customer orders. CATP identifies committed orders that must be shipped late, and calculates the additional material and capacity required to meet the committed shipment dates. These reports can be viewed though the GUI; material and capacity availability can be adjusted and the allocation can be re-run. Once the analysis of customer orders is complete, an "available to promise" schedule is created by allocating remaining resources to forecasted demand. The forecasted demand can by specified by customer class, by marketing channel, or by geographic region. Allocation decisions are made based on either economic factors (sales revenue versus manufacturing and inventory costs), or on demand priorities.

When analyzing an unforecasted order, CATP frees the resources that have been allocated to the (unconsumed) demand forecast, and re-allocates them to best meet the new order. If the customer accepts the proposed shipment schedule, then the resource are committed, and the remaining resources are allocated against the forecasted demand, producing a revised availability schedule.

Both applications run on an RS/6000 under AIX. The input data is obtained from MAPICS running on an AS/400 connected to the RS/6000. The underlying software is object-oriented, open, and highly portable. It can be interfaced with most manufacturing planning systems.

Implosion Models:

When products share common resources, production schedules for different products must be determined in a coordinated fashion. A production schedule that does not consume more than the available quantity of resources is said to be *feasible* with respect to resource availability. If the usage *rate* of resources does not depend on the quantity of product being produced, the set of feasible schedules is described by a set of linear inequalities. In general, a set of linear inequalities can have zero, one, or many feasible solutions. The implosion problem will always have at least one feasible solution, namely the "do nothing" schedule, which consumes no resources. To select the best possible feasible solution the criteria for determining "best" must be defined. Economic data, such as cost and revenue can be used to express the profit associated with a production schedule as a linear combination of the decision variables. Other criteria can also be represented, and the resulting formulation can be solved by the well-known mathematical technique of *linear programming*. Linear programming solution algorithms were developed in the 1940's, and small linear programs (LP) were solved by computer implementations as early as 1953. In the following four decades, through a combination of dramatically improved computer hardware and advances in solution algorithms, the size of linear programs (expressed as number of constraints) considered reasonable to solve has grown exponentially (Orden 1993).

Mathematical models for manufacturing planning and scheduling problems have been the focus of academic research for many years. An excellent survey is given by Nam and Logendram (1992) who note that although a wide variety of aggregate production planning techniques have been developed since the 1950's, there is still no widespread acceptance of these techniques within industry. Most LP models assume infinite overtime capacity is available, but at high cost, and determine the minimal cost multi-period production plan that can meet all demands with no stock-outs.

Although linear programming and other mathematical optimization techniques are not yet considered standard tools for manufacturing planning and control, mathematical programming applications are common in other industries. The petroleum industry's extensive use of LP-based operations planning models is often cited as a major triumph of operations research. Throughout the 1960's product blend optimization programs were used for blending gasoline, jet fuel and other distillates, and by the end of the 1960's almost all petroleum companies used some form of LP model for refinery planning (Bodington and Baker, 1990). The financial services, transportation, and communications industries accounted for many of the leading-edge applications of mathematical programming in the late 1980's (Hirshfeld, 1990).

Mathematical Formulations:

Considerable notation is required in the formulation of the general implosion problem. We present a only a single-period model here. The single-period model itself is quite useful for operational decisions, such as determining what can be produced with the resources on hand. Multi-level bills of material are considered, and each part can have one or more independent demands, having different economic factors such as profit, revenue, or backlog penalties. Our software implements a more complex multi-period model, with manufacturing lead times, BOM offsets, and substitute parts and capacities. The details are discussed in the user and reference guide.

Let J denote the set of parts (raw material, subassemblies, and end products), with

e_j = supply of part j
$a_{i,j}$ = quantity of part i required per unit of part j
H_j = holding cost per unit of part j
M_j = manufacturing cost per unit of part j.
S_r = scrapping cost per unit of part j

The values $a_{i,j}$ define the bill-of-material. We allow negative usage quantities, where producing part j creates rather than consumes a part i. This feature permits modeling co-products and by-products. Considerations such as yield and fallout can easily be incorporated by adjusting the usage rate.

Let R denote the set of capacity resources, with

c_r = quantity of resource r available.
$g_{r,j}$ = quantity of resource r required per unit of part j
Q_r = penalty per unit excess of resource r.

The values $g_{r,j}$ define the bill-of-capacity structure.

Let D denote the set of demands, with

p_d = part required for demand $d \in D$
q_d = quantity of demand d
R_d = revenue per unit of demand d
P_d = penalty per unit backlog of demand d.

The implosion model requires the following decision variables:

x_j = quantity of part j produced (only created for products, that is, parts that can be produced).
v_j = ending stock of part j
$\hat{v}_j$ = quantity of part j scrapped
u_r = quantity of resource r unused
s_d = quantity of demand d filled
b_d = backlog for demand d.

There are two or three variables per part, two variables per per demand, and one variable per capacity. In the single period model, the role of stock, scrap, and backlog is limited; in the multi-period model these variable represent the carry-over of material and demand from one period to the next. As indicated by their definitions, all of the model variables are required to be non-negative.

$$x_j \geq 0, \quad \hat{v}_j \geq 0, \quad v_j \geq 0, \qquad \forall j \in J$$
$$s_d \geq 0, \quad b_d \geq 0, \qquad \forall d \in D$$
$$u_r \geq 0 \qquad \forall r \in R$$

Backlog is defined as the quantity demanded minus the quantity shipped.

$$s_d + b_d = q_d, \quad \forall d \in D$$

For each capacity, the unused availability is equal to the original availability minus the total amount of capacity used in the production of parts. Since the leftover capacity u_r is non-negative, the production schedule cannot use more capacity than is available.

$$\sum_{j \in J} g_{r,j} x_j + u_r = c_r, \quad \forall r \in R$$

The most complex equality is the material balance constraint, which restricts the solution to using only those parts which are available.

$$\sum_{d \in D: p_d = j} s_d + \sum_{k \in J} a_{j,k} x_k + \hat{v}_j + v_j - x_j = e_j, \quad \forall j \in J$$

Initially, e_j units of part j are available; an additional x_j units are produced. This availability is used four ways: to meet independent demand of part j (given by the first sum), to meet dependent demand for part j (given by the second sum), as stock, or as scrap.

Aside from the non-negativity constraints on all of the variables, there is one constraint per part, one constraint per capacity, and one constraint per demand. This formulation can be augmented to include minimum and maximum release quantities for each part, minimum shipments per demand (or, equivalently, maximum backlog bounds), and minimum and maximum stock quantities for each part.

An objective function, based on total profit, is used to select from among the feasible solutions. The profit maximization objective function is given by:

$$MAX \sum_{d \in D} R_d s_d - \left(\sum_{j \in J} (H_j v_j + S_j \hat{v}_j + M_j x_j) + \sum_{d \in D} P_d b_d + \sum_{r \in R} Q_r u_r\right). \tag{10}$$

Alternately, one can formulate an objective function based on some notion of serviceability and an associated penalty for failing to meet serviceability targets.

Solution Methods:

One reason for the limited use of optimization methods in manufacturing is the size of the manufacturing planning problems. For 1000 parts, 500 demands, and 50 resources, the one period implosion problem has 4050 variables and 1550 complex constraints while the 25 period problem has 101,250 variables and 38,750 complex constraints. For 20,000 parts, 1000 demands, and 100 resources, the 1 period problem has 62,100 variables and 21,100 complex constraints and the 25 period problem has over a million variables and half a million constraints. Most authors recommends developing production plans at an "aggregated" product level to avoid "unmanageable" size. IBM's math programming tool, the Optimization Subroutine Library (OSL), has no inherent limits on problem size, and is recognized as having state-of-the-art solution capability. (For general information on OSL, see either the *OSL Guide and Reference* or the introductory article by Wilson and Rudin (1992).) Using OSL, it is possible to solve problems having tens of thousand or even hundreds of thousands of variables on a scientific workstation with sufficient memory and disk space (Lustig, Marsten and Shanno, 1994 and Bixby, 1994). However LP solution time does increase with problem size.

Fortunately, the special structure of the implosion problem permits problem specific pre-processing to reduce the computational burden. In addition, experience with production planners, schedulers, and material planners and participation in IBM's planning processes has lead to the development of an approximation (heuristic) procedure for rapidly determining good feasible solutions to the implosion problem. Providing OSL with a good initial implosion solution significantly decreases total solution time. These methods have proven very effective for implosion problems arising in minicomputer and personal computer manufacturing. Furthermore, once the LP has been solved, our application programming interface can be used to view the input data, the solution, and the prioritized shortage list. Demand, supply, bounds, and economic data can be revised by the user. By saving information about the computer's representation of the LP, revisions can be made directly in computer memory, and the revised problem can be solved from the previous solution, typically in a few minutes. This capability enables efficient "what-if" analysis for detailed evaluation of numerous options, such as expediting key materials, increasing capacity, and revising demand. It is anticipated that implosion capability will enable IBM to significantly improve product delivery while reducing inventory costs.

In addition to this work on implosion, the Manufacturing Logistics team has developed model-based approaches for planning under demand and supplier uncertainty for IBM manufacturing. Early pilot applications of this work as well as other models developed by the IBM Manufacturing Research department are described in by Jayaraman and Toole (1993).

For more information on IBM Production Resource Manager and related consulting and customizing services, call 1-301-432-6610.

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