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Assemble-to-Order Manufacturing: Implications For Materials Management

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EXECUTIVE SUMMARY

A company's manufacturing is often characterized as either make-to-stock (MTS), make-to-order (MTO), or assemble-to-order (ATO). This classification relates to the degree of interaction between the technological core and the market, with MTS involving the least amount of interaction and MTO the highest degree of contact. ATO represents a hybrid manufacturing strategy for which parts and subassemblies are made according to forecasts while the final assembly of the products is delayed until customer orders have been received. It is evident that each manufacturing philosophy has strategic as well as operational implications.

This paper focuses on ATO manufacturing and, in particular, on the design and operation of the manufacturing planning and control system. The relative differences between MTO, ATO, and MTS strategies, and the reasons why a company may decide to be an ATO manufacturer, are discussed first. Several problem areas, which must be addressed by a company that chooses this form of manufacturing, are then identified. It is found that the ATO philosophy requires special system design considerations, particularly in the areas of master scheduling, bills of material structuring, order entry/order promising, final assembly scheduling, and buffering against demand uncertainty. Examples of important issues discussed are the selection of appropriate master schedule units and the associated consequences for the structuring of the bills of material; the choice of efficient procedures for reliable order booking using the combined information from forecasts, confirmed orders, and the master schedule; the relationship between the final assembly schedule and the master schedule; and various techniques that can be used to counter the effects of forecast errors related to the demand for customer options.

Following the discussion of all the issues raised above and the presentation of some common solutions, actual industry applications taken from several companies are used to illustrate various aspects of ATO manufacturing. These case illustrations complement the other material since many of them were chosen to reflect alternative procedural approaches to some ATO-related problems. Finally, areas for future research into the design and operation of ATO manufacturing systems are suggested. It is particularly noted that few normative models for systems design exist in this area.

INTRODUCTION

A manufacturing company's operation can be classified as make-to-stock (MTS), assemble-to-order (ATO), or make-to-order (MTO). It is not uncommon, however, that a company belongs to more than one category, producing some products to stock and others to order. The classification is based on the degree of interaction between the firm's

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production function and the customers of the firm, with this interaction growing stronger when moving from an MTS to an MTO situation. Deciding on whether a company should produce to stock, make to order, or assemble products to order can be considered a choice of strategic importance [12, 18]. It is also a decision that strongly affects the way a company carries out its manufacturing planning and control activities [3].

This paper focuses on ATO manufacturing and its managerial implications. It discusses reasons for selecting this manufacturing policy, identifies several problem areas specifically related to manufacturing planning and control, discusses ways to solve these problems, and illustrates some of the decision areas with actual industry applications. Finally, the needs for future research in the area are identified.

ASSEMBLE-TO-ORDER MANUFACTURING

ATO manufacturing is a strategy for which standard parts, components, and subassemblies are acquired or manufactured according to forecasts, while schedules for remaining components, subassemblies, and final assembly are not executed until detailed product specifications have been derived from booked customer orders. The strategy can, thus, be located between MTS manufacturing, where products are sold "off the shelf," and MTO manufacturing, where the products are designed and produced under close collaboration between manufacturer and customer. Several essential relative characteristics of the three strategies are listed in Table 1.

MTS and MTO represent two "pure" manufacturing strategies, while ATO is a hybrid strategy. It is likely that most companies originate as either MTS or MTO firms and later, if ever, "graduate" into the ATO stage. A company starting out as an MTO firm may choose to get into ATO manufacturing because of an expanding volume and a strong similarity between some of its products. The move to ATO, thus, is done in order to capitalize on an increased demand and the possibility of reducing customer delivery times for a subset of its products.

Alternatively, an ATO firm may previously have been producing to stock. Pressured by market considerations it might have steadily broadened its product lines. A wider variety of products offered to the market, however, leads to some serious problems related to materials management:

1. The ability to forecast the sales of each individual product diminishes due to the decreasing sales per product whenever the product lines expand.
2. The inventory of finished goods, as a result, will tend to be unbalanced, with overstocking of some products and the inability to satisfy demand for others.
3. The increasing number of end items makes the master schedule difficult to manage.
4. The number of unique bills of material grows, leading to problems with maintenance and data storage.

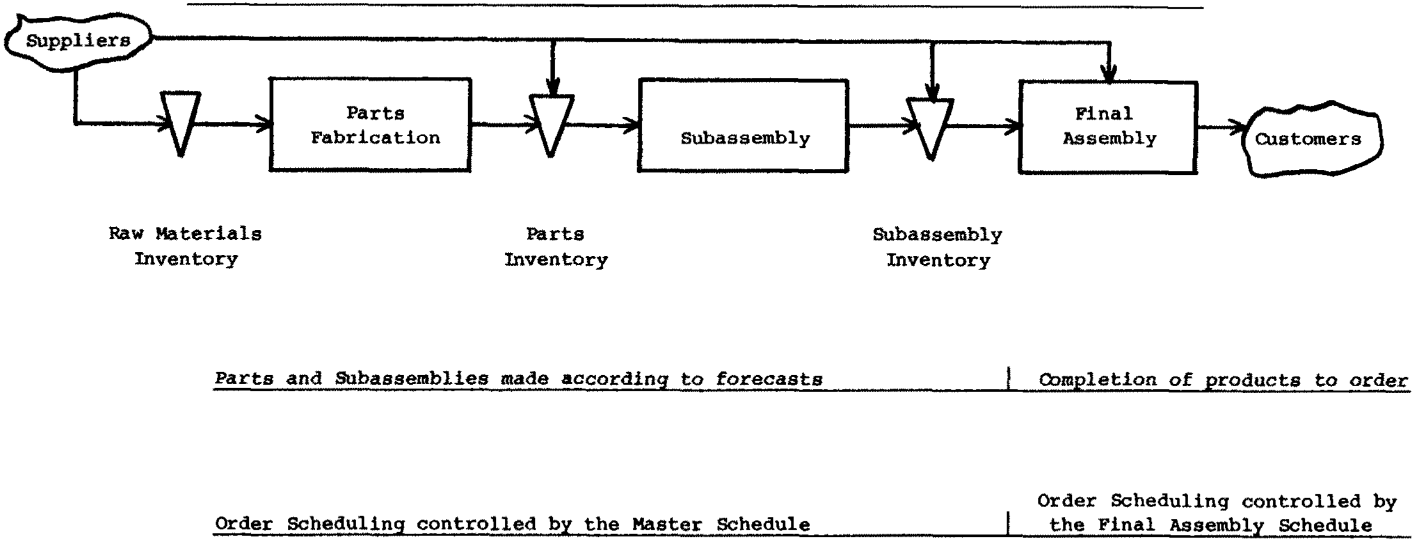
These problems, which will aggravate the commonly existing conflict between the marketing and the manufacturing functions [17], sooner or later may become so severe that the strategy of ATO is chosen. By pushing the location of inventory back in the production process and only assembling products according to customer orders (Figure 1), demand uncertainty and, thus, finished goods inventory can be reduced. In order to achieve these benefits, however, the master scheduling system must be changed, the bills

TABLE 1
Relative Characteristics of MTS, ATO, and MTO Firms

Aspect	Make-To-Stock	Assemble-To-Order	Make-To-Order
Interface between production function and customer.	Low	Medium	High
Customer delivery time.	Short	Medium	Long
Production volume of each sales unit.	High	Medium	Low
Width of product line.	Medium	High	Low
Basis for production planning and scheduling.	Forecast	Forecast and backlog	Backlog
Order Promising.	Based on available finished goods inventory	Based on availability of major subassemblies and components	Based on available capacity for manufacturing and engineering
Handling of demand uncertainty.	Safety stocks of sales units	Overplanning of components and subassemblies	Little uncertainty exists
Master Scheduling unit.	Sales unit	Major components and subassemblies	End products, major subassemblies, or stocked fabricated parts
Final Assembly Schedule.	Close correspondence to the Master Schedule	Determined by customer orders received by Order Entry	Covers most of the assembly operations
Bill of Material Structuring.	Standard B/Ms (one B/M for each sales item)	Planning B/Ms are used	B/Ms are unique and created for each customer order

of material restructured, the order entry procedures revised, and a new system for final assembly scheduling devised. Thus, the “front end” of the manufacturing planning and control system needs to be redesigned. There is also another important trade-off that a company has to make if it previously was an MTS manufacturer: in order to reduce its demand uncertainty for finished products, it must increase its customer delivery times. Whether this is acceptable or not depends upon to what extent speed of delivery is a competitive weapon and what type of customer service other companies are offering to the market. Even if delivery times will increase under ATO, the reliability of promised shipping dates are likely to increase as well and this can counter or dominate the previous effect.

FIGURE 1
A Materials Flow Diagram for an ATO Company



The basic philosophy behind ATO manufacturing is to defer "as long as possible" the commitment of material and capacity to any product, and thereby increase the flexibility of combining components and subassemblies to meet each customer order specification. The study of ATO manufacturing can conveniently be grouped into four areas—one covering the acquisition of material and the production of parts and subassemblies, another covering the interaction between the production system and the market, a third covering the assembly of the sales products, and the fourth covering the demand uncertainty aspect. Of particular interest in the first area are the design of the master scheduling system, the structuring of the bills of material, and the concomitant redefinition of the items to be forecast. The second area encompasses the order entry/order promising procedures, and the interface between the order entry, master scheduling, final assembly scheduling, and the forecasting systems. The third area deals with the design of the final assembly scheduling system. Lastly, ways to mitigate the effects of forecast errors related to customer options are treated in the fourth area.

Each of these critical areas will be further analyzed below. Due to the way the material is presented, some overlapping of the areas is unavoidable.

MASTER SCHEDULING AND BILLS OF MATERIAL STRUCTURING FOR THE ATO FIRM

One of the distinctive features of ATO manufacturing is the existence of two kinds of production schedules: the master schedule (that controls the availability of components and subassemblies, most of which are not committed to specific customers), and the final assembly schedule (that mainly relies on available components and subassemblies and controls the completion of the products, most of which are already sold). By definition, the master scheduling units for the ATO firm are located between the two extreme points represented by the raw materials/purchased components on the one hand and the final products on the other.

There are two major issues related to the design and operation of planning systems for materials (and capacity) that must be addressed by an ATO company:

1. What is the appropriate level, in a product structure sense, at which to forecast demand and to master schedule? That is, where should the "break-point" between the master schedule and the final assembly schedule be located?
2. How should the bills of material be structured in order to be compatible with the selected master schedule items and the final assembly process?

Each of these issues will be discussed in turn.

Choice of Master Scheduling Units

The master schedule represents one of the major information inputs to the material requirements planning (MRP) explosion in which requirements for lower level items are determined. Theoretically, there is a wide variety of choices for the master scheduling unit, ranging from each individual part in the inventory file to each completed sales unit. The selection depends upon many factors, such as the design of the products and how they are assembled, the extent to which common parts and subassemblies exist between various sales items, the number of master scheduling units considered to be manageable, and the ability to adequately forecast the demand for the master scheduling units. Market considerations will also have an influence, since the choice of master scheduling units will determine final assembly lead times and, therefore, customer delivery times. The primary principle used in the design of master scheduling systems is to reduce the number of scheduled units as much as possible [2, 13]. Companies in MTS, MTO and ATO situations will, therefore, position their master schedules at different levels relative to the product structures of the sales items.

Proliferation of marketable products is, for any firm, often based upon the ability to combine major components and subassemblies to generate a multitude of products. Major subassemblies are ideal as master scheduling units for ATO purposes since (a) there are only a few of them in every finished product (thus, if commonality of components and subassemblies exists between end items, the forecasting and the master scheduling effort can be reduced) and (b) they are close to the finished product, i.e., the assembly lead time and, therefore, the delivery time can be held short.

Structuring the Bills of Material

The term "bill of material structuring" usually refers to the restructuring of bills, from standard bills of material, unique to each sales item, to a situation where the modular concept of structuring is used. Modularization of bills of material entails the breaking down of products into "options," or "modules," which, in various combinations, determine the final products [4, 8, 13]. Each module consists of stand-alone subassemblies, or of kits of parts that cannot be put together until final assembly. Choosing the appropriate master scheduling unit affects the way the bills of material are structured, and vice versa (as indicated by the title of Mather's article, "Which Comes First—the Bill of Material or the Master Production Schedule?" [9]), since each master scheduling unit is also the highest level item in a bill of material.

For illustrative purposes, a simplified example (which will be used throughout the article) is shown in Table 2. The product in question is a bicycle. A customer can choose the number of gears, the kind of frame and rims, and the type of saddle. All other parts are common to all models. With three types of gears available, and two options in each of the other option groups, the possible number of different bicycles that can be manufactured is 3 × 2 × 2 × 2, or 24. Using standard bills of materials, then, 24 of these must be maintained, 24 different forecasts must be derived, and 24 different master schedules must be used.

A planning bill of material for the bike production can be devised, as illustrated in Table 3 [9, 13]. A planning bill is used for materials (and capacity) planning only, and does not represent a buildable end item. The umbrella unit can be thought of as an aggregate, or basic, bicycle, i.e., the manufactured product with no distinguishing traits assigned to it. If this unit is master scheduled, the schedule would tell only the number of bicycles that are planned to be produced per period over the planning horizon, and not the specific models. Each option group is represented on the next lower level of the bill and each choice has a percentage figure associated with it (the bills of material for each option are not shown). For example, the planning bill in Table 3 indicates that 15% of all products sold are expected to be 3-speed bikes, etc. It should be noted that not all modules are buildable. The gear module, for example, consists of individual parts that are mounted on the bicycle during final assembly. Also note that parts which are included

TABLE 2
Customer Options for a Bicycle

Gears	Frames	Saddles	Rims	Common Parts
—3 speed	—steel	—standard	—steel	—tires
—5 speed	—aluminum	—racing model	—aluminum	—brakes
—10 speed	2 choices	2 choices	2 choices	—etc.
3 choices				No choice

in all bicycles, irrespective of optional choices, have been put together in a common parts module.

With this kind of setup, the 24 different master scheduling units have been reduced to one. The advantage of this approach becomes clear if the following example is considered. Assume the company wants to offer tires as an option group. There would be two choices: standard tires and racing tires. With standard bills of material the total number of distinct bills would increase from 24 to 48. Under the planning bill approach, there would still only be one. Even if each option were individually master scheduled, the number of distinct bills would only increase from 10 to 12. For a realistic problem the savings in terms of forecasting effort, master scheduling, and bills of material maintenance could be substantial. Garwood cites an example where modularization reduced the number of bills of material from a possible 138,000 standard bills down to 40 modular bills for a specific product model [4].

Disentangling the Bills of Material

The most common problem related to bill of material structuring, and, therefore, to master scheduling, is probably the problem of "disentangling." When trying to separate standard bills into modular bills, there exist lower level items in the standard bills that are common to two or more of the options that the customers will be able to select, once the bills have been restructured. As an example, assume three end item configurations: A, B, and C (Table 4). End item A uses option 1 of option group 1 while end item B uses option 2 of option group 4. End item C, on the other hand, is made up from both

TABLE 3
A Planning Bill for Bicycle Production

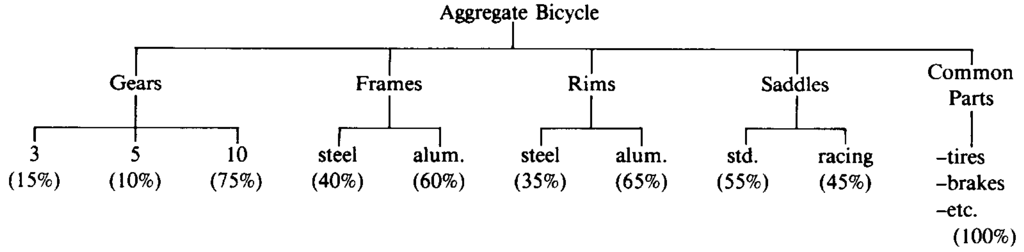
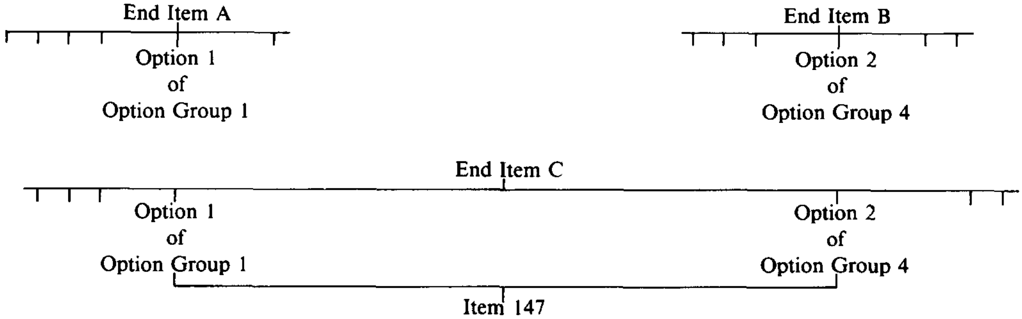


TABLE 4

An Illustration of the "Disentangling" Problem



EXAMPLE: 60% of all end items consist of Option 1 and 60% of Option 2. This could mean that 40% of the end items are of type A, 40% of type B, and 20% of type C. That is, item 147 is needed in only 20% of the units sold.

these options, and, in addition, item 147 is needed in order to complete the assembly. The problem, then, is the following: even if p% of the products sold contain option 1 of group 1 and s% contain option 2 of group 4, the percentage that contains the combination is obviously not more than the minimum of p and s, and can actually be much lower. Connections between options must be broken when creating modularized planning bills, and this must be done with consideration to the materials ordering function of the bill of material.

One solution to the example presented above is to include item 147 in the bill of material for one of the options and, therefore, overplan the usage of this item. If the item is a fabricated part, it might be redesigned to achieve a wider usage or perhaps be eliminated by redesigning the parent parts. If item 147 is an assembled item, it could be split into its next lower level parts of which some might always be used with the first option and the others with the second. The disadvantage with this approach, besides the overplanning of material that still would occur, is that it is not possible to completely assemble item 147 that is called out by the planning bill. This is an effect that is not desirable too far down in the structure since the result eventually could be just a set of individual parts. Finally, the alternative to elevate this part to a master scheduling unit status obviously exists [13].

ORDER ENTRY/ORDER PROMISING

The order entry function serves as the link between the market and the productive system. The information it receives dictates the content of the final assembly schedule, the consumption of the finished goods inventory (if any), and the revisions of the master schedule. One pertinent managerial issue in this area for an ATO firm is the following:

> What procedures are needed in order to be able to book and guarantee a customer order delivery? That is, how is order promising related to the material and capacity planning systems?

Procedures for Order Booking

Delivery performance can be measured along several dimensions. Two of the most important ones are speed and dependability. That is, how fast can the company ship an order, and how reliable is the promised shipping date? The latter variable will be discussed first.

A number of steps must be taken to ensure that a promised delivery date can be upheld:

1. Components and subassemblies that make up the customer specified product must be available in time for the final assembly operation.
2. If the components and subassemblies needed are not available at the time of booking, it must be ensured that needed capacity for fabrication and subassembly is created and that, if necessary, raw materials and component parts are acquired from outside sources.
3. Enough capacity must be available in the assembly and the testing/final inspection areas to ensure the on-time delivery.

In short, the prerequisite for reliable order promising is a reliable production planning and control system. Put more succinctly, an ATO company's delivery performance depends to a large extent on an executable master schedule and on a final assembly capacity that is in balance with the fabrication/subassembly process. To this end, the MRP system and various capacity management techniques can be used, coupled with a production activity control system for retrieving feedback information for the planning process [13, 22]. Of course, external disturbances, such as late vendor deliveries or changes in customer order specifications, will complicate an already difficult task.

If capacity planning has been satisfactorily performed, so that there is a high likelihood that the master schedule can be executed and sufficient capacity is available in the final assembly area, then order booking can be done solely against the master schedule. If a finished goods inventory or an uncommitted portion of the final assembly schedule should exist, these are, of course, consulted first.

When a sales order has been received, it has to be translated into specifications suitable for manufacturing [4, 13]. The options that the customers select are not always options that appear in the bills of material (even if this has been the case in the bicycle example discussed earlier). Rather, a combination of customer options are often needed to call out the correct material needed for assembly. Commonly, the customer will have fewer options to select than the number of master schedule modules needed to build the product.

Continuing with the bicycle example from Tables 2 and 3, a customer order for 100 racing bicycles would at order entry be translated into the need for 100 kits of common parts, 100 sets of racing saddles, 100 sets of 10-speed gears, and 100 sets each of aluminum frames and rims. The availability of the options would then, manually or by computer, be checked against the master schedule records. Parts that are controlled by the final assembly schedule (paint and decals, for example) are omitted at this time. In order to speed up the order booking procedure, components and subassemblies not considered "key" items can also be disregarded at this point. The earliest delivery date that can be quoted depends on the availability of material of all major options specified in the customer order. After each has been checked, the delivery date is set by the restricting option.

Customer service in terms of speed, i.e., how fast a shipment can be promised, is directly related to the ability to forecast the demand of various options and to have the needed material available. (There is also a type of speed related to how fast a company can respond to a customer order inquiry. This response time depends largely on the efficiency of the order booking procedures discussed above.) Another factor is the company's policy with respect to order backlogs. A long backlog of customer orders is desirable since it reduces the need to estimate the demand. The length of the backlog will, however, affect the delivery time and is therefore an important element in the customer service decision. To guard against forecast errors, buffering techniques can be employed as discussed later.

Order Entry and Time-Phased Master Schedule Records

If booking of customer orders takes place against master schedule quantities, it is natural to display both the master schedule and the actual orders in the same document. A clear identification of the uncommitted part of the master schedule undoubtedly facilitates order promising. Separate master schedule documents for aggregate units, options, and common parts kits are, furthermore, helpful to both master scheduling and order promising. Table 5 illustrates a set of time-phased records useful for this kind of two-level master scheduling [7, 15].

The top record shows the master schedule for the basic product, in this case a bicycle. Also displayed is the actual number of sold bicycles to be shipped in each period, as well as the number of units that are available to promise (ATP). The ATP-variable measures the uncommitted portion of each master schedule quantity. ATP calculations can be performed in different ways. One way is to start from the back end of the time-phased record by subtracting the actual demand for each period from the master schedule quantity that will cover them. If the difference is negative, as for period 2, ATP is set to zero and the net difference is made up from production in earlier periods (for more detail on ATP calculations, see [6, 15]).

The bottom record contains information related to one of the bicycle options, in this case the aluminum frame. This option has a forecast usage of 60%, i.e., out of 100 bicycles sold 60 are expected to have aluminum frames (also see [14]). The master schedule for frames is, in this example, set to 60% of the master schedule for the aggregate unit. The Production Forecast row shows the forecast demand for options. This data changes with the number of booked orders. In period 5, for example, there are only 27 units left to sell if the first-level master schedule is kept firm. With 60% of these expected to have aluminum frames, the production forecast for this option in period 5 is 0.60 × 27, or 17 units (for simplicity, all lead times are zero in this example and all numbers are rounded up to the nearest integer). The Projected Available Balance row is filled out just as in a standard MRP record, with the gross requirement per period being the sum of the actual demand and the production forecast (independent demand for spare parts can, of course, also be entered into these records [15]). The ATP quantities are found as earlier outlined. One difference in this second-level record is that a small inventory exists. This quantity is added to the ATP quantity for the first period.

The booking of a customer order can, with these records, take place in the following

TABLE 5
Time-Phased Records for Two-Level Master Scheduling

Aggregate Unit: the Bicycle	**Period**				
	1	2	3	4	5
Master Schedule	60	60	50	50	50
Actual Demand	54	63	36	38	23
Available to Promise	3	0	14	12	27

Option: Aluminum Frame, 60%		**Period**				
		1	2	3	4	5
Production Forecast		2	0	9	8	17
Actual Demand		30	39	24	20	12
Proj. Avail. Bal.	2	6	3	0	2	3
Available to Promise		5	0	6	10	18
Master Schedule		36	36	30	30	30

way: Assume a customer places an order for ten bicycles, of which seven come with aluminum frames. The master schedule record for bicycles indicates that an order of this magnitude cannot be shipped until period 3, although a partial delivery of three bicycles could be made immediately. Assuming that a split shipment is not desirable, the master scheduler proceeds to check the common parts record as well as each of the option records for material availability in period 3. The ATP row for the frame option in Table 5 shows that six frames can be shipped in that period. There are also, however, five uncommitted units in period 1. Thus, a total of 11 frames are available at the time of booking for shipment in period 3. (Clearly, a cumulative ATP row can facilitate order promising.) If the remaining options are available in sufficient quantity in this period, the order for ten bicycles can be booked.

The result of recording the customer order consisting of ten bicycles with seven aluminum frames is shown in Table 6. The Actual Demand row has been changed in both records, by entering ten units for the basic bicycle in period 3, and by entering seven units for the frames in the same period. With firm master schedule quantities, the number of units open for sale must be reduced accordingly. This change is reflected in the ATP rows of both records. Further, with only four more bicycles available in period 3, the production forecast for aluminum frames for this period is reduced to 4 × 0.60, or three units. Finally, the projected on-hand inventory balance for frames indicates a shortage in period 3, should the production forecast be realized. This will make the

TABLE 6
Revised MS Records Due to Order Booking

Aggregate Unit: the Bicycle	**Period**				
	1	2	3	4	5
Master schedule	60	60	50	50	50
Actual demand	54	63	46	38	23
Available to promise	3	0	4	12	27

Option: Aluminum Frame, 60%		**Period**				
		1	2	3	4	5
Production forecast		2	0	3	8	17
Actual demand		30	39	31	20	12
Proj. Avail. Bal.	2	6	3	−1	1	2
Available to promise		4	0	0	10	18
Master schedule		36	36	30	30	30

master scheduler aware that a change in the master schedule for this option might be necessary.

Fractional Requirements

One problem that is directly tied to the usage of percentage factors in the disaggregation process is the question of how to handle fractional requirements. For example, all values in the Production Forecast rows in Tables 5 and 6 have individually been rounded up to the nearest integer before they were entered. This procedure can largely overstate the requirements for options and lower level parts, especially if the fractional requirements are small to begin with. One way to solve this problem is to consider the exact cumulative production forecast and make sure that it is covered by an integer schedule at all times. This approach is illustrated in Table 7.

FINAL ASSEMBLY SCHEDULING

The final assembly schedule is the ultimate production schedule by which each end product's configuration is determined. The schedule has a shorter planning horizon, a shorter planning period, and a higher revision frequency than the master schedule. Thus, the final assembly schedule directs, commonly per hour or per day, the assembly of finished products over a one or two-week period. Also, it often initiates the ordering of materials not included in the master schedule. For example, high cost or bulky items

TABLE 7
A Method for Handling Fractional Requirements in Time-Phased MS Records

	Period				
	1	2	3	4	5
Exact production forecast	1.2	3.9	3.3	6.1	2.4
Cumulative exact production forecast	1.2	5.1	8.4	14.5	16.9
Cumulative integer production forecast	2	6[a]	9	15	17
Production forecast entered in the MS record	2	4[b]	3	6	2
Excess cumulative quantity	0.8	0.9[c]	0.6	0.5	0.1

Key:

[a] 6 = smallest integer larger, or equal to, 5.1

[b] 4 = 6 − 2 = difference between two consecutive cumulative integer forecasts

[c] 0.9 = 6 − 5.1 = difference between the cumulative integer forecast and the cumulative exact forecast, i.e., the overplanned quantity

with short lead times can be called out by the assembly schedule. Two issues are of particular interest to ATO manufacturers:

1. How is the final assembly schedule created and what is its relationship to the master schedule and order entry?
2. There comes a time when the likelihood of selling the uncommitted part of the master schedule is very small. What impact will this have on the final assembly schedule?

Creating the Final Assembly Schedule

The preparation of the final assembly schedule should be performed by the master schedulers, who have the best knowledge of the status of the master schedule. Often, the making of the assembly schedule simply consists of transferring the booked orders from the master schedule and sequencing them. Unique bills of material for the final operations, based on the customer order specifications, are then needed to create pick lists for the components and subassemblies of each final product. The same manufacturing bills of material are, of course, also needed to describe the final product for assembly instruction purposes. Orders for which material is missing are usually not entered into the final schedule.

The Dynamics of Master Scheduling in an ATO Firm

As the master schedule rolls through time, it will, in succession, lead to the ordering of purchased material, initiate fabrication and the subassembling of parts, and finally reach the point where the schedule must be closed and replaced by the final assembly schedule. One interesting management problem relates to the explicit or implicit time-fence set by the assembly lead time. If not all of the aggregate units in the first-level master schedule have been committed to customer orders at this stage, a decision must be made whether to drop the uncommitted portion from the schedule or build units to stock. If the latter alternative is chosen, someone must decide (usually marketing) which units to produce out of all the variants possible. These decisions are especially significant for firms whose products are too costly to rework once they have been completed.

BUFFERING TECHNIQUES FOR ATO FIRMS

Protection against demand uncertainty logically takes place where the demand is forecast. Thus, for an ATO company, buffers should exist at the option level in the planning bills of material. By keeping buffer stocks of optional components and subassemblies but not of common parts, the flexibility to meet various customer order specifications increases, while the maximum production volume of finished products is unchanged.

Several alternative buffering techniques are possible in connection with planning bills of material. The buffers that are introduced affect the second-level master schedule either directly or indirectly, depending on how this master schedule is determined. Three different ways of creating the master schedule are proposed here:

1. The master schedule on the option level is found as a percentage factor multiplied by the master schedule for the aggregate unit.
2. The master schedule quantities on the option level are found for each period as the sum of the production forecast and the actual demand.
3. The master schedule on the option level is a set of firm planned orders determined by a master scheduler. The information in the Project Available Balance row will play an instrumental role in determining the master schedule.

Given these approaches to master scheduling, a number of ways to buffer against uncertainty can be suggested:

1. Increase the master schedule for the aggregate unit.
2. Increase the percentage factor that determines the master schedule for the option from the aggregate master schedule.
3. Increase the lower level master schedule directly.
4. Increase the percentage factor that determines the production forecast for the option.
5. Increase the production forecast directly.
6. Maintain a safety stock of options that is subtracted from the current on-hand inventory when the Projected Available Balance row is determined.
7. Create buffer stocks by the use of a hedging technique.

The first technique is clearly not recommended since it leads to an unintentional overstatement of the total production volume. Even if the actual aggregate output level is, in fact, kept at its original level, this approach will overplan for all options, as well as for common parts. A disadvantage with the second and the third techniques is that they do not automatically recognize the decreased uncertainty every time an order is booked and the forecast is consumed. Thus, if the master schedule for the aggregate unit is fully booked, there is obviously no need to overplan at the option level [8, 10].

The fourth alternative will automatically account for the reduction in uncertainty by the way the production forecasts are calculated. In the bicycle example presented earlier (Tables 5 and 6), the master schedule for the frames was initially found as the percentage factor multiplied by the master schedule for the basic unit. As time goes by and orders are booked, the discrepancy between the original forecast and the actual outcome will become evident from the Projected Available Balance row. Positive numbers in this row can be viewed as buffers against demand exceeding the production forecast. Thus, if overplanning using the percentage factors does not take place, the Projected Available Balance row will make any unplanned inventory clearly visible. On the other hand, if overplanning through the percentage factors is taking place, the buffer should be reflected in a positive projected on-hand inventory (also see Hyster in [2]). The fifth method is similar to the previous one, except that it requires manual intervention from the master scheduler.

The sixth technique is straightforward. It simply adjusts the on-hand inventory balance so that the safety stock quantity is preserved. The method is only viable if the master schedule is determined from the Projected Available Balance information. Further, to use the technique it should be desirable to physically store the material that constitutes the option in question.

The seventh and last method can most adequately be described as a "buffering philosophy" and can as such be used in conjunction with all techniques mentioned above, except number six. Normally, forecast accuracy diminishes the further out in the future one tries to forecast. For the near future, on the other hand, companies can many times rely on backlogs, making forecast information unnecessary. This indicates that buffers, if entered into the master schedule, should vary over the planning horizon and be positively correlated with the distance to the period being forecast. Also, the further out in the master schedule the buffer appears, the less expensive is it to maintain the resulting safety stock. This is due to the way in which value is added to the products during the manufacturing process. If a buffer quantity is added to the master schedule just inside the total cumulative production lead time, and kept in the same relative position over time, the effect is restricted to a build-up of purchased material. If the buffer is moved closer in, the production of parts and subassemblies is instigated [10].

Hedging as a buffering technique, then, means that varying buffer levels are kept over the planning horizon. The technique can obviously be practiced in various ways, one of the simplest being the approach of maintaining a constant buffer outside a certain time fence, and no buffer inside the fence. It should be observed that the technique is self-purging. If, for example, a hedge is maintained in the same relative position in the master schedule and the material that has been ordered as a result of the hedge is not consumed, the material build-up will disappear during the next MRP explosion (see Miller [11] for a closer discussion of the consequences of hedging).

CASE ILLUSTRATIONS

The discussion related to the design aspects of ATO manufacturing planning and control systems can be enriched by also illustrating alternative solutions taken from industrial firms. The cited examples touch upon all areas discussed earlier. They do not intend to illustrate either good or bad management practices—just alternative management practices.

Illustration 1

ATO manufacturing can lead to an excessive number of master schedule units if too many options are controlled directly by the master schedule. One company's solution to this problem is presented below [19].

The Volvo Truck Division in Sweden had experienced a rapid and almost exponential growth in master scheduling units over a number of years. In some cases, up to four different options selectable by the customer had to be combined before the complete material requirements were determined. For example, in order to know the material specifications for brakes, it was necessary to know not only the brake type option, but also the wheel dimension and whether left hand or right hand drive had been selected. Another example: to call out the material needed for the rear lights of the truck, the rear light option and the wheel base option were needed. These two options in combination would specify the contents of a third module, consisting of fasteners and cables of varying lengths. In order to reduce the ever increasing number of such master scheduled "combination options," an ABC analysis was performed on all inventory items. It turned out that 50% of the items accounted for only 2.4% of the annual usage and 70% of the items accounted for 7.5% of the annual usage, etc. It was further found that eliminating 70% of the low usage parts from the MRP system reduced the number of master scheduling units by 50% (at the time, the number of items in the master schedule was well over 6,000). The removed parts were put on reorder point systems and the change has led not only to simplified master scheduling but also to an increased availability of the parts that previously were master scheduled.

Illustration 2

It is possible to combine the demand forecasting of options with standard bills of materials, as is illustrated by this case. It is also shown, however, that this interesting approach, in general, produces a less favorable customer service level than does the planning bill approach.

Creating modular bills of material is necessary in order to reduce the number of master scheduling units. An obvious trade-off is the effort involved in the restructuring of the bills of material. Further, since planning bills are simply umbrella units that hold together numerous modules, another set of bills of material is needed to direct the assembly of these modules and thus the completion of the products. In order to avoid the bill of material restructuring problem, one electric company developed what they call a "product characteristic forecasting" procedure for their low volume items that involves the use of standard bills of material [1]. The method will be illustrated here by using the bicycle example from Table 3. Assume that the aggregate forecast calls for a production of 100 bicycles per week. Assume further that the forecast for options shows that 15% of the sales represent 3-speed bikes, 10% are 5-speed bikes, and 75% are 10-speed bikes, etc. The complete option forecast is shown in the bottom row of Table 8. Also assume that each of the 24 possible bicycles that can be built has a unique catalogue model number associated with it (for simplicity, these numbers run consecutively from 1 through 24 in Table 8). It can be shown, using a fairly simple allocation procedure [1], that it is enough to master schedule only six of the 24 different bicycles, with quantities given in the rightmost column of Table 8, in order to ensure the availability of the material needed to meet the forecasts (the procedure does not always generate unique solutions).

TABLE 8
An Illustration of the "Production Characteristics" Forecasting Procedure

Catalogue Model Number	Gears			Frame		Rims		Saddle		Quantity needed/week
	3	5	10	Steel	Alum	Steel	Alum	Std	Racing	
1	×			×		×		×		15
2		×			×	×		×		10
3	×				×		×		×	
4			×	×		×			×	10
• • •										
10		×			×	×		×		
11			×	×			×		×	15
• • •										
20			×		×		×		×	20
21	×			×			×		×	
• • •										
24			×		×		×	×		30
	15%	10%	75%	40%	60%	35%	65%	55%	45%	100 units/week

Check: 40 steel frames are needed per week. They will be ordered as follows:

15	through catalogue model # 1
10	through catalogue model # 4
15	through catalogue model #11
40	steel frames

The advantages of this procedure for the company are the following: the firm can keep its standard bills of material, one for each of the 24 bicycles, and the restructuring effort is avoided; and, there is no need to forecast sales of each individual catalogue model. Instead, only the product characteristics (the options) and the total number of units sold are forecast. Since forecasting takes place at a higher level of aggregation, it is likely that the forecast accuracy will increase. It should be noted that the intention is not to build the units that are entered into the master schedule. The reason for scheduling these units is only to order lower level material. The method, thus, does not eliminate the final assembly schedule based on acccepted customer orders.

King, who calls this procedure "the covering set" approach (since the standard bills chosen to be master scheduled completely cover the total material requirements), has investigated its mechanics in his dissertation and also compared the method to the planning bill approach described earlier [6]. His hypothesis is that since common parts can be planned separately and do not require any safety stock when ordered through planning bills, this method leads to higher customer service (i.e., shorter delivery lead time) for the same safety stock investment than does the covering set approach. The reason for this is that common parts are overplanned with the latter method since they are represented in each product. As a matter of fact, all options in a product will be overplanned if its master schedule quantity is increased. For example, assume that in order to buffer against forecast errors related to 3-speed gears, 5 more bikes of catalogue model number 1 are master scheduled per week. The result of this will be more protection for steel frames, steel rims, and standard saddles, as well as for 3-speed gears (see Table 8), but it will also increase the inventory of common parts. This inventory is redundant if the aggregate output is fixed to 100 units per week. King's simulation study confirms that, for the same amount of buffer inventory, the planning bill approach outperforms the covering set approach in a variety of environments [6].

Illustrations 3 and 4

The following case examples show the ways two ATO firms have resolved some design issues in the areas of master scheduling, order promising, and final assembly scheduling [21].

The Trane Company

The Trane Company is a large manufacturer of heating and cooling equipment. It master schedules 471 models, each with its own two-level percentage bill of material. (A two-level percentage bill is a planning bill of material that addresses the option-within-option problem. Thus, the master schedules for options appearing at levels 1 and 2 in the product structure are determined by percentage factors multiplied by the respective parent master schedules.) The company has dedicated production lines to ensure the availability of key parts and subassemblies. These 450 key items, which appear as lower level items in the planning bills of material, are master scheduled by using the firm planned order capability of the MRP program. This means that the MRP explosion will not change the timing and sizing of the manually determined planned order releases for these items. In effect, then, master scheduling takes place at several levels in the bills of material. This achieves smoothed production rates for the key items, with accompanied high rates of schedule completions and high levels of capacity utilization.

A customer that orders a unit that is not stocked by Trane must normally choose a configuration based on 23 classes of options. A unique bill of material is created for each customer order. This bill is exploded into its parts and the parts list is given to the master schedulers. It is their task to check the availability of critical components (by consulting the master schedules) before a shipping date for the order can be set. All critical items checked in this way are scheduled using the firm planned order technique referred to earlier.

The company operates with a 12 week time fence. Outside this time fence the master schedule consists of a mixture of confirmed orders and forecasts. Explosion of this part of the master schedule takes place through the planning bills of material. However, once inside the 12 week time fence only booked customer orders exist on the master schedule. Thus, all uncommitted units are eliminated from the schedule at this time and the remaining booked orders are exploded through their exact bills of material.

The making of the final assembly schedule at Trane is the responsibility of the master schedulers. The schedule extends for one month, is made up monthly, and is mostly very close to the master schedule on which it is based. The execution of the final assembly schedule is monitored daily with progress reports. Minor revisions to the schedule take place continuously due to problems in manufacturing, insufficient material or capacity, or due to customer generated changes in shipping dates.

Steelcase, Inc.

Steelcase, Inc. is a multi-plant office furniture manufacturer operating in a repetitive manufacturing mode. Unlike Trane, it uses a two-level master scheduling system. This system, however, differs from the one described in Tables 5 and 6 in that ATP information is not used in connection with the schedule that represents the input to the MRP system. Instead, the second-level master schedule is dynamically adjusted by letting the master schedule quantities per period equal the sum of the actual demand and the production forecast. That is, if this approach was used in Table 5, the resulting master schedule for the frame over the planning horizon would be 32, 39, 33, 28, and 29 units, respectively.

The company has a sophisticated computerized order scheduling system that ties together different product lines produced at a number of local plants. If a customer order consists of products from several plants, the order scheduling system checks the first availability date for all products in the order before a shipping date is set. The complete customer order is later consolidated and shipped from a central warehouse.

For each plant, customer orders are booked against the overall production plan and against master schedules for product groups (first-level master schedules). These plans and schedules are stated in an aggregate unit of capacity. Over and under bookings at the production plan level are accepted within a +5% to a −2% range while a ±10% deviation is allowed at the product group level. No check of available material takes place before order acceptance.

Steelcase uses a cyclic scheduling system for final assembly operations. This means that a fixed schedule, covering the day the scheduling procedure starts (last day in each week for new order entries) and until the orders are shipped 15 working days later, is repeated every week. Five of these days are used for detailed order preparation and order scheduling, and the rest are used for subassembly of parts, finishing operations, and packing. Daily computerized production schedules are created for each department, outlining the operations to be performed and the quantities needed. These schedules are tied together in a cyclical fashion so that parts that are welded one day can be painted the next day and assembled the third day, etc. Since the high volume production involves relatively simple products, based on standard parts with high commonality, parts and subassemblies are not tied to particular customer orders until the very end of the assembly process. Manufacturing for stock usually takes place if the production plan and the product group master schedules are booked short of their lower target levels, comes the cut-off time for the final assembly schedule generation.

Illustration 5

Buffering against demand uncertainty at the master schedule level can obviously be done in many different ways—including using no buffers at all. At the Trane Company and Steelcase, Inc., for example, overplanning of options do not take place. The company discussed below, on the other hand, is an interesting example of how one ATO manufacturer manages its buffers.

The Tennant Company, a manufacturer of industrial floor maintenance equipment, is a company that practices hedging, has visible buffers, and lets the master schedulers manage the allocation of these buffers [2]. A buffer quantity is first determined as a percentage of the sum of the master schedule quantities falling between two time fences. The buffer is manually entered into the records by the master schedulers and distributed over the same time period. The buffer is printed on a separate row in the master schedule document, making it highly visible. The computer further prints an exception message should the hedge quantity between the time fences fall short of the planned quantity. If there is no need for the buffered material, the hedges will disappear once they roll inside the closest time fence.

AREAS FOR FUTURE RESEARCH

Several fertile areas open to ATO-connected research can be identified. These areas deal with both the strategic and the operational aspects of ATO manufacturing.

1. There are potential advantages, as well as disadvantages, associated with ATO manufacturing. One major issue relates to the question of when benefits resulting from this strategy exceed the costs. That is, under what circumstances should a company start out as an ATO manufacturer, or, if already in an MTS or MTO situation, switch to this philosophy? Can the strategic consequences of increasing the customer lead time while, at the same time, offering a wider variety of products, be quantified? Can the cost of restructuring the bills of material, changing the procedures for master scheduling, order entry, and final assembly scheduling be estimated and weighted against a reduced total inventory investment (also see the research issues related to buffering)? Are there other trade-offs involved that need to be identified and evaluated?
2. The issue of bills of material structuring is crucial to ATO manufacturing. Yet very little research have been done in this area to date. For example, how should modules be defined to achieve the most versatile use (for an analytical approach to this problem, see [16]) and how is this versatility traded off against an increased number of master scheduling units? How do different approaches to structuring affect various performance measures, (see [6])? What is the impact on product proliferation from parts commonality resulting from standardizing parts and designing new products around existing modules? That is, will the solution to the problem of product proliferation create an even larger product variety? What effect will the higher production volumes made possible through an emphasis on commonality and modularization have on the manufacturing process [20]?
3. The issue of safety stocks in multi-level inventory systems is not a well researched

area. Particularly for ATO firms, two questions are of interest: What procedures should be used to dimension the buffers for various options, considering that the demands for options are not independent? Further, what is the impact of commonality on the investment in buffer stocks? It is clear that the fewer the number of stocking points, the less buffer inventory is needed for the same protection. Can this in itself be an argument for adopting the ATO strategy?

4. Final assembly scheduling is a topic that has received little attention in the literature. There seem to be, however, a few interesting issues related to the making of the assembly schedule: How to maximize the use of available material at the time the schedule is prepared? Also, how should orders be sequenced with respect to customer preference and material/manufacturing considerations?
5. A final area relates to forecasting and the consumption of forecasts in an ATO setting. The procedure for determining the production forecasts discussed earlier, a common industry approach, is clearly "memoryless." The fraction of future orders requiring a certain option is constant, irrespective of the number of units already booked. Are there other procedures for short-term forecast revisions that are more appropriate?

The scarcity of research related to the important areas outlined above indicates that despite the fact that there exists a general body of knowledge related to manufacturing planning and control systems, little research effort has been devoted to the development of normative models for systems design. This type of research is clearly needed in order to be able to determine an appropriate manufacturing strategy and in order to design planning and control systems that fit the tasks specified by the chosen strategy [12].

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