METHOD FOR ESTIMATING A LEAD TIME OF A PROCESS

FIELD OF THE INVENTION

This invention relates to a method for estimating a lead time of a process. In particular, this method is suitable for estimating or forecasting a lead time for manufacturing a product or providing a service, depending on the urgency of delivery.

BACKGROUND OF THE INVENTION

Business is competitive. Whether it is in the production of a product or the provision of a service, customers are interested in timing and cost. Sometimes the two are at least partly interlinked, especially when it comes to the planning of inventory and storage. Thus modern business, where systems can be quite complex relies increasingly on thorough planning and good execution.

Over the past three decades, many systems have been commercially implemented. Initially, only material planning was initiated, but it has since become more complex, including the integration of vendors. In present day systems, entire resource planning and scheduling are necessary and further approaches are proposed to improve these activities.

Some of the main approaches currently in use are the Materials Requirements Planning (MRP), Manufacturing Resource Planning (MRPII) and Enterprise Resource Planning (ERP) systems. MRP is a software system for planning materials to arrive at the point of manufacturing just-in-time (JIT). MRPII improves on the MRP system and includes labour, machine and vendor requirements in manufacturing resources planning. ERP is a further enhanced software system for managing the entire operation of a manufacturing enterprise and includes all transactions required for supporting its operation. One of its major drawbacks is its fixed lead time. Attempts have been made to address this, for instance, by adding a Finite Capacity Scheduling (FCS) and Advanced Planning & Scheduling (APS) system as a module in MRP/ERP. FCS and APS are software systems designed to integrate with ERP and MRP systems to enhance the short term production planning and scheduling systems that are notoriously inadequate in MRP

systems. However, FCS/APS cannot solve this problem in some situations. This is mainly because of the complexity or dynamic state of the manufacturing systems.

Enterprise Resource Planning (ERP) is an extension of MRP and MRPII. MRP systems were initially designed for use in the United States of America when labour cost was the highest cost component in manufacturing costs there. Therefore, the focus of MRP was to schedule the required materials to arrive at the point of use at the right time, thereby minimising inventory costs and maximising labour efficiency and productivity.

However, MRP assumes infinite capacity on a shop floor, and this often leads to problems in manufacturing resource planning. Its extension to MRPII was implemented by adding Rough-Cut Capacity Planning and Capacity Requirements Planning, besides other modules, to improve the use of MRP. However, it did nothing to solve the capacity management problem of the traditional MRP environments.

ERP adds functionality to MRP, and allows integration of vendors, customers, and distributors into the MRPII information network. However, even with these improvements in resource planning, the planning module in ERP remains the same as that in MRP, which has remained unchanged for the last 30 years.

There is something fundamentally wrong with the concept of ERP/MRP. The key underlying bases of ERP/MRP are still performed by using fixed lead times and backward scheduling from product delivery dates with the wrong assumption of infinite shop floor capacity.

APS extends the power of FCS, which includes material availability as one of the manufacturing constraints, and allows planning of new product deliveries from prospective sales. However, FCS methodology still predominates the basis for scheduling in APS.

A FCS system assumes infinite material availability or obtains historical material availability data from the MRP system. These lead to drawbacks in FCS. Further, it makes many assumptions, such as process times being known and deterministic; materials being available, etc., and provides unreliable information during the initial planning stage of production. It is too unreliable, time consuming and over-demanding

for use in high level planning stages. This is also because the value of detailed scheduling decreases rapidly after two to three weeks in a dynamic manufacturing environment.

Even with widespread support for APS, it is still very difficult to integrate ERP and APS because of their diverse assumptions or objectives:

Long-term or mid-term Planning in ERP vs. short-term scheduling in APS.

Infinite capacity planning in ERP vs. Finite capacity scheduling in APS.

Planning in ERP assumes that its plan is always feasible when scheduling.

No support from APS's capacity scheduling module to improve planning in ERP system.

It is, therefore, not possible to use MRP/MRPII/ERP, FCS/APS or ERP+APS to estimate a lead time to complete a process for producing a product or providing a service during high level initial planning stages efficiently. This is because MRP/MRPII/ERP treat lead times as a constant, and this assumption is no longer valid.

FCS/APS endeavours to calculate the lead time more accurately, but it is impossible in most situations due to the dynamic manufacturing environment as well as the lack of accurate data during the early planning stages. ERP+APS is a new direction in manufacturing resource planning but the problems of integrating these two systems have not been overcome.

Lead time estimation/forecast is very important, but it has been ignored for years.

Scenario 1 illustrates a typical process of securing a customer order:

Scenario 1. *A salesman for a manufacturer prepares a quote for a client. The salesman enters some basic information about the client's requirement into a computer, and the system produces a formal standard contract specifying the product's configuration, price, and delivery date.*

When the client accepts the quote, the system records the order; schedules the shipment; reserves the necessary materials from inventory; orders needed parts from suppliers, and plans the manufacturing and assembly processes in the factories.

The main problem in Scenario 1 is how to provide a reasonably accurate delivery date in real time to the client upon request. This delivery date should be as short as possible to reflect the competitiveness of the company, and it should not be too short so as not to lose credit because of late deliveries. This is very important because it is very difficult for the planner and/or scheduler to overcome problems during later manufacturing stages when the product lead time has not been properly estimated during the initial planning stages. Current practices do not support this kind of functionality.

MRP/MRPH/ERP assumes a fixed lead time, say three months, and instantly provides a delivery date to the client. As MRP/MRPII/ERP does not consider shop floor loading when using fixed process lead times, it must be longer than necessary in order that the estimated product lead time is on the conservative side.

The FCS/APS approach requires information about product structures, process times, materials status and the anticipated shop floor capacity several months in advance. It uses finite capacity scheduling to find a feasible schedule and calculates a lead time based on this schedule. However, it is very difficult to obtain these data with reasonable accuracy during the planning stage several months in advance in a manufacturing environment. Detailed schedules older than two or three weeks become unreliable.

ERP+APS also cannot help much during the product planning stage because it either uses the fixed lead time of ERP or the historical shop floor capacity of PCS to calculate a product lead time. Both methods are not suitable for estimating/forecasting lead time during the product planning stage when accurate data are not available.

SUMMARY OF THE INVENTION

An aim of the present invention is thus to provide a new lead time estimating method and system. The aim is to estimate a lead time, for manufacturing a product, providing a service, etc, taking into consideration current capacity (or other relevant considerations) more easily, reliably and/or efficiently.

According to one aspect of the present invention, there is provided a method for use in estimating a lead time for a process which has one or more operation steps, using a

proposed process schedule that indicates a proposed capacity profile for at least one of the one or more operation steps, which capacity profile includes capacity requirements for one or more other processes which share at least one of said at least one of the one or more operation steps, said method comprising the steps of:

(a) identifying proposed capacity requirements within said proposed capacity profiles that exceed a maximum capacity resource criterion as infeasible;

(b) repairing identified infeasible proposed capacity requirements with steps aimed at making them feasible;

(c) updating said proposed process schedule with any repairs in step (b);

(d) identifying proposed capacity requirements within said proposed capacity profiles that are below the maximum capacity resource criterion but above a critical capacity resource criterion as infeasible;

(e) repairing the infeasible proposed capacity requirements with steps aimed at making them feasible;

(f) updating said proposed process schedule with any repairs in step (e); and

(g) returning to step (a) or (d) if repairs were made in step (e); else

(h) outputting a proposed process schedule.

Step (e) may comprise identifying the proposed capacity requirements within said proposed capacity profiles that are below the maximum capacity resource criterion but above the critical capacity resource criterion as critical, and then determining whether the critical proposed capacity requirements are deemed infeasible based on a further criterion.

The repairing step or steps may comprise moving excess requirements to one or more other operation time periods.

The repairing step or steps may comprise moving the excess requirements forward or backward to the one or more time periods.

The repairing step or steps may comprise dividing the excess requirements and moving some to different time operation periods.

The repairing step or steps may comprise moving some of the divided excess

requirements forwards and some of the divided excess requirements backwards.

The repairing step or steps may comprises moving excess requirements to one or more other operation steps by alternative routing.

The repairing step or steps may comprise proposing a modification of resources to change the total capacity for an infeasible operation step, thereby changing the maximum and/or critical capacity resource criteria for said operation step.

The repairing step or steps may comprise proposing a modification of resources to outsource at least some of the requirements of an infeasible operation step.

The method may further comprise conducting a backward estimation of the lead time based on an actual agreed delivery date of the process.

The lead time may be estimated forward from a current date or backward from an actual agreed delivery date of the process.

BRIEF DESCRIPTION OF THE, DRAWINGS

The present invention will be further described by way of non-limitative examples with reference to the accompanying drawings, in which:

Figure 1 illustrates the use of the Forward and Backward Lead Time Estimators for obtaining an order and then planning a shop floor production capacity upon receipt of that order;

Figure 2 illustrates the workflow of an exemplary Forward Lead Time Estimator incorporating the present invention;

Figure 3 illustrates the workflow of an exemplary Backward Lead Time Estimator incorporating the present invention;

Figure 4 illustrates a Bill of Materials as used in an example of the present invention;

Figure 5 illustrates a forward schedule for some of the processes in an example of the present invention;

Figure 6 illustrates initial capacity conditions for two work centres in the example;

Figure 7 illustrates modified capacity conditions for the two work centres of Figure 6, taking into account routings in the example;

Figure 8 illustrates a move forward repair technique;

Figure 9 illustrates a move backward repair technique; and

Figure 10 illustrates a Gantt chart for Finite Capacity Scheduling.

DETAILED DESCRIPTION OF THE INVENTION

The present invention will now be exemplified by a method for estimating a lead time for manufacturing a product or providing a service (a Forward Lead Time Estimator) and a method for working out the schedule and plan, once a delivery date has been fixed (Backward Lead Time Estimator). These are used to integrate planning and scheduling functions during a production or service initial planning stage.

In general, the present invention is herein described in terms of manufacturing runs.

However, it is not limited thereto. For instance it could be used in estimating a consultancy project time, litigation and many other services commercially or otherwise, in offices, government, education and so on.

In typical use of the present invention, when a customer's enquiry is received, a salesman enters some basic information about the customer's product configuration into a computer. The Forward Lead Time Estimator of the invention then works out some possible delivery dates, such as a normal delivery date, an express delivery date or an earliest possible delivery date, etc. based on current shop floor and other conditions. The salesman then provides the customer with a time quotation, following which the cost and delivery date can be negotiated. The actual delivery date may not necessarily be the same as any one of the possible delivery dates quoted; it may be a later date, or one in between.

Once an order is confirmed, the Backward Lead Time Estimator is employed, internally, to find a production schedule based on the confirmed delivery date. Materials required are planned and booked and the production capacities, such as men and machines, are reserved.

In practice, a salesman may require delivery dates and corresponding prices in real time, say within several minutes, so that he can promptly quote these to the customer. Sometimes, it takes a little longer to determine the three categories of delivery date mentioned above, and the customer may not be willing to wait any longer. In such a case, this method of estimating a delivery date is employed to generate a delivery date, say a normal delivery date promptly, so that the salesman can prepare a quote for negotiation while the Forward Lead Time Estimator continues to find other feasible delivery dates for later negotiations.

For example, suppose the Forward Lead Time Estimator produced a normal delivery date is 1st Oct., the express delivery date is 15th Sept. and the earliest delivery date is 10th Sept., each corresponding to a particular production schedule. After negotiation with the customer, the actually delivery date is fixed as 25th Sept., which is earlier than the normal delivery date but later than the express delivery date. For actual production, if the plan used to arrive at the express delivery date is adopted, inventory will increase unnecessarily early. If all activities in the plan corresponding to normal delivery date are

simply moved forward by 6 days instead, this plan may not be feasible. Thus the Backward Lead Time Estimator is used to determine the final plan, based on the confirmed delivery date.

Figure 1 illustrates the use of the Forward and Backward Lead Time Estimators for obtaining an order and then planning a shop floor production capacity upon receipt of that order.

In step S1, a potential customer order is received. In step S2, the Forward Lead Time Estimator is used to provide possible delivery dates, according to the urgency required. Step S3 sees negotiation with the customer over the actual delivery date (and cost). The order is then confirmed in step S4. Finally, the actual production schedule is planned through use of the Backward Lead Time Estimator, allowing capacity to be reserved and materials ordering to be planned.

This flow is only exemplary. The order may change; for instance, the Backward Lead Time Estimator may be used before the order is confirmed. It may not even be needed if one of the actual proposed dates is chosen.

Figure 2 illustrates the workflow of an exemplary Forward Lead Time Estimator.

S102 (Start) represents the starting point of this operation. In this step S102, the type of business scenario is determined. It is classified either as a normal order; an urgent order; or a priority order (e.g. from a very important client) etc. An appropriate lead time parameter, k, between 1 and 3, is then assigned depending on the urgency of delivery being worked on or planned.

In step S104 (Initialise), process and material information and constraints are inputted, and details of key processes and materials are processed based on the type of order, i.e. urgency of delivery determined in step S102. For example, a key material is theoretically available within 4 weeks from overseas, or within 2 weeks if extra fees are paid when an order is urgent.

In step S106 (Generate Lowest Queue Time), the earliest possible start dates of the key processes or earliest shipping dates of key materials are determined (irrespective of

current capacities), and the theoretical process or move times required for each step in manufacturing this product are modified by the lead time parameter, k as follows:

Initial process lead time = k x (theoretical process time + Setup Time) --- Equation 1

Totalling the "Initial process lead time" for every process along the critical path in the production run provides what is effectively a first estimate of the lead time for the process (e.g. the time from the present to delivery to the customer). Once all the process times of non-key resources, and the earliest possible start dates of key resources and their process/move times have been worked out, a forward process schedule is generated in step S108 (Forward Schedule), with the assumption of infinitely available capacities at the point of planning. This forward process schedule includes details of currently accepted and proposed throughput on all affected work-centres.

In step S110 (Generate Bottleneck Capacity Profile), bottleneck work centres are identified within the forward process schedule worked out in step S108. Every process has a maximum capacity. If that is exceeded or approached, it becomes a potential bottleneck. In practice, however, there are usually only a few processes that approach capacity. Two thresholds: a high and a low threshold, are set for each work-centre to determine whether a work-centre will reach its critical capacity at any time. If the capacity at a work-centre is identified as going to be above its high threshold at any particular time period, then this work-centre is considered to be a bottleneck, with an infeasible capacity plan.

The bottleneck identification procedure used in this exemplary Lead Time Estimator is slightly different from known bottleneck procedures. In actual practice, bottleneck resources may change states over a short period of time. In order not to miscalculate a potential bottleneck, the bottleneck identification procedure in step S110 includes all potential bottleneck resources in this invention. The potential number of bottleneck resources considered is, therefore, larger than the number that other current bottleneck scheduling methods may consider, and may even be larger than is necessary, but this is useful to ensure that all possible bottlenecks are considered during this initial planning stage. Otherwise, a possible neglected bottleneck resource could result in an infeasible production plan.

In step S112 (Use Repair Method to Balance the Capacity), the capacity at each bottleneck work centre is examined and alternative solutions are sought to resolve this overloading problem. This is done by employing a repair method, for example, by moving a portion of the bottleneck capacity forward, or backward; or dividing a portion of the bottleneck capacity between two or more time periods, either forward, backward or a combination of forward and backward time periods. The technique of dividing a bottleneck capacity between several time periods is known as interchange repair.

After any infeasible capacity plans have been resolved or balanced, the altered forward schedule is examined in step S114 (Identify Critical Time Periods) to identify any critical capacity periods. Critical capacity periods are those where the proposed throughput for a particular period does not reach the high threshold mentioned above, but does exceed the low threshold. Such critical capacity periods need to be looked at more closely to determine whether they are feasible.

In step S116 (Critical Time Periods Found?), a decision is made whether any critical capacity periods exist. If there is no critical capacity period, the forward process schedule is deemed feasible and in step S118 (Define Lead Time), the Estimator outputs the overall lead time result, possibly together with a breakdown of the processes and possibly even the costs of production (which may then be used for production management variance analysis), and the operation ends at step S120 (End).

If any critical capacity period is identified in step S116, the process branches from Step S116 to step S122 (Zoom in to Critical Periods), where the process then focuses on each of them. In step S124 (FCS to Generate Schedule), these proposed capacities are compared with the available or finite capacities at the shop floor by employing a known scheduling routine. This routine examines each critical process according to different sets of scheduling rules, such as Shortest Processing Time, Earliest Due Date, Minimum Slack Time, Weighted Shortest Processing Time, and so on. Each set of scheduling rules is examined one by one automatically until a feasible schedule is found and the required capacities for fulfilling the proposed customer order can be accommodated within the finite capacities at the shop floor.

A decision is then made in step S126 (Feasible?) on the resulting altered schedule as to whether it is feasible. If it is found to be so, the process moves to step S118, where it

outputs the overall lead time result, etc and the operation ends at step S120. If it is not feasible, the unfeasible processes are identified as such.

After iterating through all the scheduling rules in step S124 and the plan is not found to be feasible in step S126, the capacities in the critical process periods which are not feasible are subject to repair, at step S128 (Use Repair Method to Balance the Capacity), using forward, backward or interchange repair techniques discussed earlier, and the operation then reverts to step S114.

The repair techniques employed in steps S112 and S128 are identical. However, the identification of what requires repairing is different. In step S112, repair is used to resolve the capacity loading above the high threshold level (without considering the shop floor loading), whilst in step S128 repair is used to resolve the capacity problem when a capacity cannot be accommodated within the shop floor schedule after all possible scheduling rules have been checked.

The operation then restarts at step S114, with any of the steps S116 to S128 possible again until a feasible process plan is found within the finite capacities of the shop floor. Although not shown here, the process includes a count to stop, if no feasible plan can be produced after a predetermined number of iterations.

This Forward Lead Time Estimator operation is repeated for all the required classes of delivery order, if required, and alternative yet feasible lead time estimates are provided for the customer.

Certain rules apply to the operation of the Forward Lead Time Estimator of this embodiment, and especially to the repair and rescheduling operations. Repair of particular periods does not necessarily mean just moving around the jobs of the proposed new order. It may mean moving around existing orders.

For working out a normal delivery plan, all existing planned and confirmed processes at the shop floor cannot be changed. The theoretical process time is calculated based on key materials being obtained using normal lead times and a larger initial lead time parameter, $k \cong 3$ is chosen. Forward scheduling is used to find an initial production schedule based on these and is then tested. If capacity problems are identified, a

forward repair scheme is employed to provide a feasible plan, that is, by moving operations with capacity problems to a later date to resolve the capacity problem. It is expected that this procedure will generate a longer lead time, but the computation cost is kept low. This is still highly desired because the salesman can provide a normal delivery date to the customer promptly and this scheme will not have much adverse impact on any existing shop floor production plans for a particular time.

For working out an express delivery plan, all existing planned processes with confirmed orders cannot be changed. The theoretical process time is calculated based on key materials being obtained using some express lead times. A smaller initial lead time parameter, $k \cong 2$ is used and the resulting initial forward schedule tested. With a preferred shorter time and rearrangement of some existing entries possible, more complicated balancing of the shop floor capacity is necessary and complex repair schemes, such as move backward, interchange, etc. are used.

For working out an earliest possible delivery plan, all existing planned processes (confirmed or otherwise), except those that are part of existing confirmed earliest possible delivery plans can be re-planned when necessary. The theoretical process time is calculated based on key materials being obtained using the shortest possible lead times. The initial lead time parameter is set as $k \cong 1$. When capacity problems are identified, repair schemes are used to balance existing planned capacity first, and the proposed schedule of the present order being worked on is changed only when no other feasible production plan can be accommodated within the finite capacity of the shop floor.

Evidently, the urgency of delivery will translate to different product prices. Cost estimation based on different delivery scenarios is then provided to the salesman for negotiation with a prospective customer.

In order to execute this Forward Lead Time Estimator, several parameters, such as initial lead time parameter, type of repair scheme, key resource and material lead times, and so on, are determined. Optimisation methods, such as genetic algorithms may be employed to find some near-optimal scenarios for determining some of these parameters.

The initial Lead Time should be as low as possible so as to reduce the lead time, but it should not be too low so as not to effect the performance.

In the above, the initial lead time is worked out using the theoretical processing time. An alternative approach would be to calculate it using a portion of the fixed lead-time in an existing production system. In the latter approach, an altered lead time modifier k` with a value of less than 1 would be used.

Once the lead time is agreed (e.g. through agreement of a delivery date), it is necessary to work out an actual production schedule. Figure 3 illustrates the workflow of a Backward Lead Time Estimator which does this.

Step S202 (Start) represents the starting point of the Backward Lead Time Estimator.

The delivery date has been confirmed, and the latest reasonable start date for each constituent process to fulfil this order have to be determined, within the available or finite capacities of the shop floor. The process and material information and constraints are inputted in step S204 (Initialise), and the processes and materials timings are to be planned according to the urgency of delivery already promised.

In step S206 (Generate Lowest Queue Time), the latest possible start dates of the processes and latest move dates of materials are determined, and the theoretical process or move times are modified by a similar lead time parameter, k discussed earlier. This k can be the same as the previous k, but the agreed lead time is not be used here; it is not imported to the backward lead time estimator. After negotiation, the agreed (forward) lead time is discarded, because this lead time is estimated based on the assumption of providing products as early as possible. Such a lead time could lead to unnecessary high inventory.

In order to reduce inventory, a backward lead time estimator based on the confirmed due date is introduced to delay production as long as the due date is met, so as to minimise inventory. Thus in the same way the forward estimator uses a start date, usually "today", to work forwards from, so the backward estimator works backward from the agreed due date.

After all the process times of non-key resources, and the latest possible start dates of key resources and their process/move times have been worked out in step S206, a backward schedule is generated in step S208 (Backward Schedule). Backward scheduling is a technique for calculating operation start dates and due dates starting with the due date for the order and working backward to determine the required start date and/or due dates for each operation.

In step S210 (Generate Bottleneck Capacity Profile), the capacity profile at each work centre is generated and any bottlenecks are identified. As in step S110 in the Forward Estimator, a high threshold is set, and a process period is considered bottleneck if the capacity under planning is above the high threshold.

In step S212 (Use Repair Method to Balance the Capacity), the bottleneck periods are resolved by moving a portion of the infeasible capacity or capacities forward, backward or in a divided manner between two or more time periods, as in step S112 of the Forward Estimator process.

In step S214 (Identify Critical Time Periods), the repaired process schedule is examined and any critical time periods, if any, are identified. As in step S114 of the Forward Estimator process, this is based on a low threshold.

In step S216 (Critical Time Period Found), a decision is made whether any critical time periods exist. If there are none, this backward scheduling plan is deemed feasible and the lead time for the last start date of production to fulfil the present customer is outputted in step S218 (Define Lead Time) and the required resources and production capacity are reserved in step 219 (Reserve Corresponding Capacity). The process then ends at step S220 (End).

If any critical capacity periods found in step S216, these periods are examined in step S222 (Zoom in to Critical Periods). In step S224 (FCS to Generate Schedule), the capacity in these periods are compared with the available capacity at the shop floor and examined according to some scheduling rules as in step S124 of the Forward Estimator Process. After a feasible backward schedule is found or all the scheduling rules have been used to examine the critical capacity processes, a decision is made at step S226 (Feasible?) as to whether the proposed plan is feasible.

If the backward schedule can fit within the finite capacities of the shop floor in step S226, the schedule is feasible and a lead time result is output in step S218 and the required capacities for this order are reserved in step S219.

If no feasible schedule is found in step S226, any unfeasible critical capacities are sent for repair, with portions of overloaded capacities moved to other time periods in step S228 (Use Repair Method to Balance the Capacity). After this, operation of this Backward Estimator moves back to step S214 and the repaired schedule is examined to identify any critical process periods that might still exist.

The operation then proceeds as before from step S214, through to step S228, until a backward scheduling plan within the finite capacities of the shop floor is found. It is most unlikely, if not impossible for there to be no feasible plan available if the lead time is no shorter than the earliest possible lead time estimate given in the forward estimator process.

The repairs and scheduling of the Backward Lead Time Estimator operation may result in existing plans having portions rescheduled. If that happens, those entire plans may need rescheduling. Backward scheduling aims to see that the process is delayed as long as possible, without taking risks and needing to make urgent orders. In this way, money for materials can be paid out as late as possible.

The Forward and a Backward Lead Time Estimator operations contain many similar, if not identical process steps. This is necessary to ensure that a completion date that is offered as feasible by forward estimation is found to be feasible by backward planning. What may change between them is the order of strategies to be used (at least in the repair steps).

The above estimator processes are not limited in use to when new orders are in the offing. By providing both a Forward and a Backward Lead Time Estimator, a shop floor production plan can be revised periodically, using either procedure or a combination of both procedures. The gap between the forward and backward lead times generated can be used to indicate the buffer capacity the shop floor has during a particular period of planning. This buffer capacity may be appropriately used to overcome emergency

capacity problems, for example when machines break down, to ensure that operation of the shop floor is not severely interrupted and an optimum level is maintained.

The Forward Lead Time Estimator process is also suitable for forecasting a shop floor production capacity. This only requires minor changes to the rules of operation. This forecasting procedure is similar to planning customer orders, except that only normal delivery dates are generated and the planned capacities are used as forecasts. These forecasted or reserved capacities can be made available for other late customer orders when a need arises. Key material requirements can also be forecasted in this manner, allowing purchasing to be delayed for as long as possible.

The Lead Time Estimator of the present invention can be employed as an alternative to the capacity planning module in MRP.

The Forward Lead Time Estimator serves as an alternative to Rough Cut Capacity Planning (RCCP) in MRP, for verifying the Master Production Plan, and the Backward Lead Time Estimator serves as an alternative of Capacity Requirements Planning (CRP) in MRP. By considering the shop floor capacity (at least within the current planning period) and variable process lead times (depending on the urgency of the order being worked on/planned), these Lead Time Estimators can be very useful in today's competitive and dynamic commercial environments.

To illustrate the operation of an embodiment of this invention, a worked example of a shop floor with seven work centres is used. Each work centre has one or more machines and a capacity of 550 hours per week, and there are 16 customer orders with specific bills of material, customer delivery dates, and so on, already in the production system. Table 1 shows details of the machines in each work centre.

Work Centres	Machines
Milling/Drilling/Grinding Work Centre	Drilling Machine
	Grinding Machine
Hardening Work Centre	Hardening Machine 01
	Hardening Machine 02
CNC Work Centre	CNC Machine
Wire Cut Work Centre	Wire Cut Machine
EDM Work Centre	EDM Machine
Fitting/Assembly Work Centre	Fitting/Assembly Machine 01
	Fitting/Assembly Machine 02
	Fitting/Assembly Machine 03
Polishing Work Centre	Polishing Machine 01
	Polishing Machine 02

Table 1: Machines at the work centres

The current shop floor capacity condition is healthy, and the current production plan is feasible, when a new customer order is secured. A bill of materials for the new order is shown in Figure 4. The Bill of Materials is a list of all the items used in the production of the new order, including such items as part identification and the quantity of the different components. The key for Figure 4 can be seen in Table 2 below.

10	J020002	Core Main	1	Piece
12	J020003	Core Insert	1	Piece
14	J020005	Core Slider	1	Piece
16	J010002	Cavity Main	1	Piece
18	J010003	Cavity Insert	1	Piece
20	J020001	Core	1	Piece
22	J010001	Cavity	1	Piece
24	J000000	Mould A End Assembly	1	Piece

Table 2 – Bill of Materials

From Figure 4, there are two sub-assemblies in the final assembly, namely Core and Cavity. Core consists of three components, that is Core Main, Core Insert, and Core

Slider, and Cavity consists of two components: Cavity Main, and Cavity Insert.

In order to generate a production plan, we also need routings for all components, which are assumed with detailed information. Routing contains the specific steps required to produce a particular component. Each step in the routing is called an operation, and each operation generally requires machine and labour. Table 5 shows the routings required to produce two of the parts (namely, cavity main and cavity) of this product, which are identified in Figure 4 and Table 2.

Routing					
Part Number		J010002			
Part Description		Cavity Main			
No.	**Work Centre**	**Setup Time (Hours)**	**Processing Time (Hours)**	**Fixed Lead Time (Days)**	**Operation Description**
					Release
10	CNC	3	10	3	CNC Roughing
20	Hardening	5	15	5	Hardening
30	Drilling/Grinding	1	5	2	Grinding
40	CNC	1	3	2	CNC Finishing
50	EDM	2	6	3	EDM
60	Polishing	4	15	5	Polishing
					Store

Routing					
Part Number		J010001			
Part Description		Cavity			
No.	**Work Centre**	**Setup Time (Hours)**	**Processing Time (Hours)**	**Fixed Lead Time (Days)**	**Operation Description**
10	Fitting/Assembly	4	20	5	Fitting & Assembly
					Store

Table 3: Routing of Parts: Cavity Main and Cavity

Table 3 shows the routing for the component Cavity Main. There are 6 operations to produce the Cavity Main, namely: CNC Roughing, Hardening, Grinding, CNC Finishing, EDM and Polishing. These operations require CNC, Hardening, Drilling/Grinding, CNC,

EDM and Polishing work centres respectively. The "No." column provides information about process sequencing. Processes are conducted in process number sequence, starting with the lowest process number. The processing times are also specified in the routing.

Table 3 also shows the routing for the component Cavity, which consists of only one operation, which requires the Fitting/Assembly work centre for 20 hours. This process involves a setup time of 4 hours and a fixed lead time of 5 days.

In routing, the fixed lead time is a span of time usually required to perform an operation or a series of operations. As is quite clear from these routings, the lead time is very much greater than the combined setup and processing times. This is quite normal in job shops, where parts usually spend 90% of their lead times waiting in queues.

With the above information, the Forward Lead Time Estimator is used to estimate some possible delivery due dates and to find a correspondingly feasible process schedule. With reference to Figure 2, the following steps of operation are illustrated:

Step S104: Initialising process and move times for all tasks required to complete order.

All processes and material move times are identified and determined. This includes the information shown in Table 3 for each routing.

Step S106: Determining earliest process start dates.

The urgency of this order has been determined in step S102 and the key processes and materials required have been identified in step S104. In this step, the information entered in step S104 is used to work out the earliest start dates and processing time of each process, including the move times of all the materials required.

For example for the cavity, which is one of the steps in processing the final assembly, there is a fixed lead time of 5 days for a processing time of only 20 hours.

For this order, with equation 1, we could use k = 2, i.e. the estimator is set to estimate an express delivery. Using equation 1 given earlier and the theoretical processing time of

20 hours and the setup time of 4 hours, the initial lead time for this process is 2 x (20+4) hours, giving an initial lead time of 48 hours or roughly two days.

An alternative approach is to use:

Initial process lead time = k` x (Fixed Lead Time) --- Equation 2,

Where k` is a parameter between 0 and 1.

k` is not more than 1 because Fixed Lead Time is normally pretty long compared with the actual processing time (for example one week as opposed to 6 hours). The reason to have such a long lead time is that Fixed Lead Time does not consider capacity constraints and extra safe time is included in the Fixed lead time. In most situations, this fixed lead time should be long enough for processing, and it is much longer than actual lead time. The present invention is useful for providing a realistic estimation based on the shop floor capacity conditions, which is normally much shorter that the Fixed Lead Time. If k` were set to a number more than 1, then in theory, this initial lead time should be always enough for processing, thus no further adjustments are required. In this case, the result of this invention will be worse than traditional Fixed Lead Time approaches.

0 is, in fact impossible; k` should, in practice, be no lower than 0.2. The Fixed Lead Time is a typical period for completing a process operation. This data may come from an existing database of the current MRP/ERP system in use or it may be derived from past shop floor records or statistical analysis thereof. Using Equation 2 in this example instead, we calculate the initial lead times using the fixed lead time given in the routing tables, that is 5 days. Supposing the parameter k` is 0.5, multiplying the two numbers, the initial estimate arrived at is 3 days. The results from the different calculation approaches are quite different, although not hugely so. It does not matter as this is just an initial estimate.

Similarly, we can also calculate the initial lead time for all process steps.

Step S108: Forward Scheduling.

Based on calculated initial lead times for all process steps, a forward scheduling

algorithm will be performed. The start date will by default be set to the date when the system is running. The user can also modify it to a date when the current order is supposed to be confirmed. With a known or given start date, the processing times, and by following the process constraints entered in step S104, the process operations are arranged in logical order of completion and a forward schedule is thus generated.

Forward scheduling is a scheduling technique where the scheduler proceeds from a known start date and computes the completion date for an order, usually proceeding from the first operation to the last.

The following illustrates the initial forward scheduling for the component Cavity Main.

As is indicated in Table 3, there are six operations to produce the Cavity Main, namely: CNC Roughing, Hardening, Grinding, CNC Finishing, EDM, and Polishing, with fixed lead times of 3, 5, 2, 2, 3 and 5 days respectively. Using a parameter of 0.5, as above, the initial lead times come out as 2, 3, 1, 1, 2 and 3 days for these operations.

Suppose production starts on 1 Aug, the forward schedule for the Cavity Main would be as shown in Figure 5. The reference numbers below are not the process numbers of Table 3, but the reference numbers in Figure 5.

From 1 to 2 Aug, CNC Roughing operation 30 will be processed by CNC work centre;

From 3 to 5 Aug, Hardening operation 32 will be processed by Hardening work centre;

On 6 Aug, Grinding operation 34 will be processed by Drilling/Grinding work centre;

On 7 Aug, CNC Finishing operation 36 will be processed by CNC work centre;

From 8 to 9 Aug, EDM operation 38 will be processed by EDM work centre;

From 10 to 12 Aug, Polishing operation 40 will be processed by Polishing work centre;

By the end of 12 Aug, the component Cavity Main should be ready for assembly.

The next step in the process, as shown by the Bill of Materials is the Cavity Routing, using the component Cavity Main. As mentioned above, this gives rise to an initial lead time of 3 days. Thus the "Cavity" processing can take place from 13 to 15 Aug, with a Fitting and Assembly operation processed by the Fitting/Assembly work centre.

In step S110, the bottleneck capacity profile is generated. In this shop floor, the CNC work centre and the Fitting/Assembly work centre tend to provide the bottlenecks, which means their output determines the output of this shop floor. The other work centres always have enough capacity to finish their jobs on time. Therefore, the rest of this example focuses only on these two work centres and ignore all other work centres.

Figure 6 shows the shop floor capacity conditions for the CNC and the Fitting/Assembly work centres prior to this new order. Figure 7 then shows the modified capacity profile for these two just taking into account the above Cavity Main and Cavity Routings. CNC roughing adds 3+10= 13 hours (Setup time + Processing Time), CNC finishing adds 1+3 = 4 hours and Fitting and Assembly adds 4+20=24 (see Table 3).

As Figure 7 shows, the CNC work centre upper threshold capacity is 500 hours. During the week of 29 Jul to 4 Aug it reaches over 750 hours, which is above the upper threshold. With this plan it will be over capacity during this period. Consequently, this plan is infeasible and corrective action is needed to make it feasible. This bottleneck is identified in step S110 and sent for repair in step S112. Although the Fitting/Assembly work centre is recognised as critical, in this plan, it has nothing over the upper threshold in this identified period and thus does not (yet) need repairing.

Step S112 therefore employs a suitable repair technique to make the plan feasible.

Step S128: Repair-based process planning.

Repair based planning is employed to solve capacity overloading or plan unfeasibility problems. Several repair techniques, such as move forward repair strategy, move backward repair strategy and interchange repair strategy, may be used. Figure 8 illustrates a move forward technique. Here the 13 hours of Main Cavity processing time in week 3 can be moved forward to week 4 as there is plenty of spare capacity in that week. In particular, it is moved to 5 and 6 Aug. As the second CNC operation on the

Main Cavity, the CNC Finishing operation occurs five days later (see Figure 5), it too must be moved, to 11 Aug, which is still in week 4. Giving a total throughput for that week as 17 hours.

Although it does not happen in this example, Figure 9 illustrates a move backward technique that can sometimes be used. The trouble in this instance would be that it would load the preceding week, week 2 up to near the upper threshold. It is impossible for a move back or forward to put a week up over the upper threshold. The proposal would be assessed and rejected by the repair process, and other repair strategies would be employed. But it is possible to put a week up over the lower threshold, which means this week becomes critical too. Whether this move can be accepted or not will be determined by finite scheduling.

If move forward, move backward and division techniques do not provide a feasible plan, taking into account what existing elements can and cannot be moved, other possible repair techniques include: outsourcing, which means some process steps are carried out by a third party in order to resolve a bottleneck capacity; overtime, which means available capacity is increased to meet the capacity requirement; or alternative routing, which transfers some of the production capacity to alternative work centres to alleviate the burden of a bottleneck resource.

Once such infeasible weeks have been repaired, step S114 determines if there are any critical weeks in the revised plan shown in Figure 8. These are defined as those weeks where the required capacity is higher than the lower threshold.

In weeks 7 and 9, the required capacity of the CNC work centre is 500 hours, which is higher than the lower threshold but does not exceed the upper threshold. These periods are considered critical and a feasible plan is not guaranteed. Further verification in step S124 against the finite capacities at the shop floor is necessary. For the other weeks in the CNC operation and all the weeks in the Fitting and Assembly operation, the required capacity is not critical. Available capacity is sufficient and a feasible plan is guaranteed.

Step S124: Verify schedule's feasibility using Finite Capacity Scheduling.

The estimator process identifies any critical periods in step S114. It zooms in on these in

step S122. Up to that point, it has been looking at everything on a generalised scale, in macro. Steps S122 and S124 take a micro view, looking at the specific process in detail. Finite Capacity Scheduling is employed in this step to examine whether the shop floor capacity can deploy the resources required for each critical time period to make this schedule feasible.

Relevant information is passed to a scheduling routine, and separate scheduling rules and different scheduling techniques, such as local search, Tabu search, constraint programming etc. will be tested to see whether it is feasible. For example, a Tabu search is a meta-heuristic superimposed on another heuristic. The overall approach is to avoid entrainment in cycles by forbidding or penalising moves which take the solution, in the next iteration, to points in the solution space previously visited.

Different scheduling techniques, such as Shortest Processing Time, Longest Process Time Earliest Due Dates, Minimum Slack Times, and Weighted Shortest Processing Time, etc. are then used to examine the schedule's feasibility. In practice, separate scheduling rules are tried one by one automatically, in a preferred order, until a feasible schedule is found. If all scheduling rules have been used and no feasible process schedule is found, then the schedule is not feasible and corrective repair techniques are necessary in step S128. This step has available to it the same techniques as step S112.

In this instance, although both weeks 3 and 7 are critical and are reviewed in step S124, only week 7 is illustrated in Figure 10, which is a Gantt chart for the Finite Capacity Scheduling to verify plan feasibility. Finite capacity scheduling techniques are employed to find a feasible schedule. Figure 10 shows a feasible schedule. Although the CNC machine in the Gantt Chart is pretty busy, it still can finish all operations on time. Therefore, the plan for week 7 is feasible and no adjustment is required.

Steps S114, S116 and S122 to S128 may be repeated until all infeasible and critical process times are resolved and a feasible schedule is found. Once this is done, a feasible delivery due date is outputted (and the corresponding processing costs may also become available). This Forward Lead Time Estimator can also provide other feasible delivery due dates based on a spread of initial parameters, for instance a normal delivery date of 20 Aug, an express delivery date of 15th Aug. and an earliest delivery date of 10th Aug.

The salesman negotiates with the customer to find the customer due date, say 25 Aug 2002. Based on this due date, the backward approach is then employed for optimising overall enterprise resource utilisation, if necessary, and the necessary resources/materials are reserved/booked so that this order can be fulfilled and delivered on time.

The backward approach follows the much the same line as the forward approach, except that a backward scheduling technique is employed in step S208 instead of the forward scheduling technique.

The Forward and Backward Lead Time Estimators can be embodied in software which, for use, is loaded onto an individual computer or onto a network. For network use, existing plans and repair and scheduling rules can be kept in a central server or database, accessible from one or more nodes. Thus salesmen can derive proposals at customers' offices through a modem link or the like.

By providing a method for estimating the overall lead time to manufacture a product, this Forward Lead Time Estimator is very useful process planning tool and a feasible process schedule can be worked out during the initial planning stages, especially when accurate process capacity data is not available and a reasonably accurate quotation has to be provided to the customer promptly.

Steps S108 to S114 of the Forward Estimator and S208 to S214 of the Backward Estimator can together be termed as "Infinite Planning", i.e. initial capacity planning does not consider the capacity available for performing each process operation. These embodiments of the present invention then use finite scheduling in steps S124 and S224 to verify such infinite planning during critical time periods. Thus they combine infinite planning and finite scheduling to find a feasible plan efficiently.

Some advantages of the embodied inventions are:

it is a planning tool which utilises FCS to improve the plan quality;

it provides a mechanism to find lead time under different situations;

it focuses on some critical time periods, bottleneck resources and key materials;

it is able to use the lowest possible initial lead time and iteratively increase it;

it is able to combine Forward and Backward Lead Time Estimator to find a quality plan;

it is able to provide different possible delivery dates as well as corresponding costs to help a salesman to make good decisions during negotiation; and

it is able to provide a co-operative mechanism to protect concurrent clients running lead time estimators from conflicts.

The present invention provides methodology to improve planning decision-making. The invention can help current MRP/MRPII/ERP systems to integrate better with APS/FCS. It is an alternative or an improvement on MRP/MRPII/ERP's planning mechanism. The output of this method can be downloaded to a FCS/APS system to generate short-term detailed schedules. Concurrent users can be integrated to avoid capacity conflicts.

The invention is also very useful in MRP/MRPII/ERP as well as Supply Chain Management systems to improve their planning modules significantly.

While only few embodiments of the present invention have been described and their operations illustrated, it is understood that many changes, modifications and variations could be made to the present invention without departing from the scope of this invention. Whilst the present invention has been described with reference to a manufacturing environment, it is clearly applicable to any other service processes that require some form of planning for their efficient execution.

CLAIMS

1. A method for use in estimating a lead time for a process which has one or more operation steps, using a proposed process schedule that indicates a proposed capacity profile for at least one of the one or more operation steps, which capacity profile includes capacity requirements for one or more other processes which share at least one of said at least one of the one or more operation steps, said method comprising the steps of:

(a) identifying proposed capacity requirements within said proposed capacity profiles that exceed a maximum capacity resource criterion as infeasible;

(b) repairing identified infeasible proposed capacity requirements with steps aimed at making them feasible;

(c) updating said proposed process schedule with any repairs in step (b);

(d) identifying proposed capacity requirements within said proposed capacity profiles that are below the maximum capacity resource criterion but above a critical capacity resource criterion as infeasible;

(e) repairing the infeasible proposed capacity requirements with steps aimed at making them feasible;

(f) updating said proposed process schedule with any repairs in step (e); and

(g) returning to step (a) or (d) if repairs were made in step (e); else

(h) outputting a proposed process schedule.

2. A method according to claim 1, wherein step (e) comprises identifying the proposed capacity requirements within said proposed capacity profiles that are below the maximum capacity resource criterion but above the critical capacity resource criterion as critical, and then determining whether the critical proposed capacity requirements are deemed infeasible based on a further criterion.

3. A method according to claim 1 or 2, wherein the repairing step or steps comprises moving excess requirements to one or more other operation time periods.

4. A method according to claim 3, wherein the repairing step or steps comprises moving the excess requirements forward or backward to the one or more time periods.

5. A method according to claims 3 or 4, wherein the repairing step or steps comprises dividing the excess requirements and moving some to different time operation periods.

6. A method according to claim 5, wherein the repairing step or steps comprises moving some of the divided excess requirements forwards and some of the divided excess requirements backwards.

7. A method according to any one of the preceding claims, wherein the repairing step or steps comprises moving excess requirements to one or more other operation steps by alternative routing.

8. A method according to any one of the preceding claims, wherein the repairing step or steps comprises proposing a modification of resources to change the total capacity for an infeasible operation step, thereby changing the maximum and/or critical capacity resource criteria for said operation step.

9. A method according to any one of the preceding claims, wherein the repairing step or steps comprises proposing a modification of resources to outsource at least some of the requirements of an infeasible operation step.

10. A method according to any one of the preceding claims, further comprising conducting a backward estimation of the lead time based on an actual agreed delivery date of the process.

11. A method according to any one of claims 1 to 9, wherein the lead time is estimated forward from a current date or backward from an actual agreed delivery date of the process.

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(71) Applicant *(for all designated States except US)*: **SINGAPORE INSTITUTE OF MANUFACTURING TECHNOLOGY** [SG/SG]; 71 Nanyang Drive, Singapore 638075 (SG).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **XU, Sheng** [CN/SG]; Blk 908, Jurong West Street 91, #10-217, Singapore 640908 (SG). **LENDERMANN, Peter** [DE/SG]; Blk 20, Bukit Batok Street 52, #21-01, Singapore 659244 (SG). **GOH, Kiah, Mok** [SG/SG]; Blk 654 Senja Road #17-254, Singapore 670654 (SG).

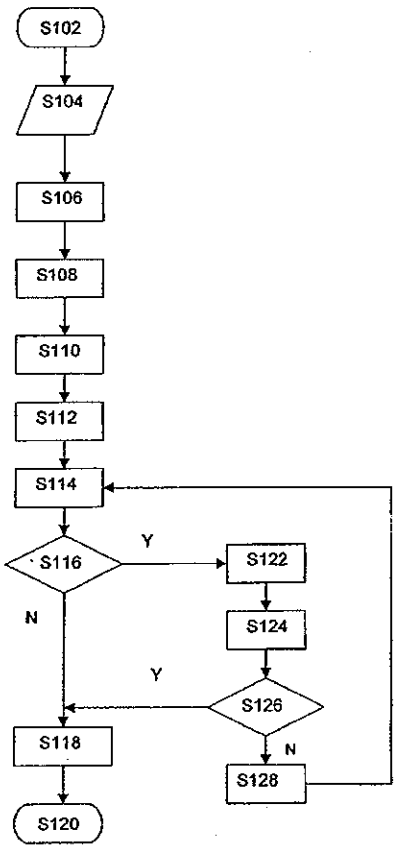
(74) Agent: **ELLA CHEONG MIRANDAH & SPRUSONS PTE LTD**; Robinson Road Post Office, P.O. Box 1531, Singapore 903031 (SG).

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(54) Title: METHOD FOR ESTIMATING A LEAD TIME OF A PROCESS



(57) Abstract: This invention provides a method for estimating a lead time of a process. This lead time may be that for a normal delivery, express delivery, earliest possible delivery, and so on. This lead time is necessary before a reasonably accurate quotation or process planning can be provided. A process capacity profile is first generated for each constituent process step. Any infeasible capacities within the capacity profile are identified and repaired. Likewise any critical cpacities are identified and repaired if necessary.

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