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**A New Approach to MRP
Functioning in Make-to-Order
Manufacturing**

by

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IN MAKE-TO-ORDER MANUFACTURE**

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Executive Summary

The unique requirements in the industry dealing with long lead time, custom-made products cannot be satisfied by either MRP or Critical Path systems alone, but necessitate a combination of features of both. MRP is capable of handling manufacturing tasks in great detail, but it is not designed to accommodate non-material related items. Further, schedules generated by MRP do not reflect the flexibility desired in varying amounts in every manufacturing contract. Critical Path, else known as Network Analysis, can handle activities of any nature. It provides flexibility in scheduling activity and caters for resource and cash flow scheduling and other features usually not present in typical MRP systems. A combined MRP/Network Analysis system for use in a make-to-order manufacturing environment is described.

The paper examines the above issues in detail and presents the experience gained from a leading compressor manufacturer whose most functional requirements were finally met by the proposed model.

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1. Introduction

The unique requirements of the make-to-order manufacturing environment have for too long been neglected in the rush to develop and implement computerized software tools. Make-to-order manufacture, which is characterized by highly sophisticated products, very small lot sizes (typically one), long lead times and high levels of customization and customer interaction, lies somewhere in the region between job-shop manufacturing and project work. Accordingly, software systems developed for these two applications, like Material Requirements Planning (MRP) and Network Analysis systems such as Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT), respectively, are only partially suited to the make-to-order environment.

MRP primarily aims at improving the production and inventory management functions of manufacturing, by providing a time phased material plan for a required production schedule. MRP promises such improvements as lower inventories, reduced delivery times, higher stock-turn ratio and improved customer satisfaction. While MRP in its present form is largely adequate for the tasks involved in batch manufacturing, several shortcomings become apparent when it is applied to a make-to-order environment. Chief among these shortcomings is the lack of two way time analysis during scheduling. MRP performs only a backward time pass, beginning at the level of the end product and working backward through the Bill of Material (BOM) structure, which results in a schedule comprising only of so-called "late times," i.e., the latest possible times at which events must occur in order to meet the required end product

delivery date.

Another shortcoming is presented by the structural restrictions in the BOM for MRP analysis. Elements in the BOM must have a material content and must be arranged so that the structure only explodes downward from the end product; upward explosion is prohibited.

These restrictions prevent the applicability of MRP in cases where long lead times and a high degree of uncertainty make a two way time analysis beneficial, if not essential. Further, the extensive customer interfacing and other non-material-related activities, including pre-and post-manufacturing tasks involved in custom-made products cannot be scheduled by MRP or included in a product's BOM. Other typical make-to-order type of activities, such as temporary assembly, testing and subsequent break-down of assemblies for further processing, likewise violate the BOM format because they require upward explosions.

Project planning/scheduling, by a form of Network Analysis such as CPM or PERT, is far more flexible in both of the above issues. These techniques, unlike MRP, utilize a two-way time analysis, which produces both "early" and "late" times for activities and identifies the activities that are critical to the project versus those that have some slack time. Further, the project network, which, like the BOM in MRP, functions as the foundation of the system, has a much less restricted structure than a BOM. Elements in the network represent activities, which may or may not have materials, resources and costs associated with them. In addition, links between activities may occur in any logical arrangement, providing for the less common relationships occasionally encountered in make-to-order operations.

Network Analysis, however, does not provide the production and inventory management capabilities of MRP, making it unacceptable as the sole controlling system in a make-to-order environment.

Efficient control of make-to-order manufacture necessitates a system combining features of both MRP and Network Analysis. In spite of the large number of operations where such a system could be used (e.g., Department of Defense contracts, large equipment manufacturing, and so on), there appears to be little research in this area. The idea of combining CPM and MRP has been presented in the literature [1,8,9], but in these cases it is described in the context of project work, (i.e., incorporating MRP logic into Network Analysis), rather than in the context of manufacturing. Further, these strategies fail to achieve the full benefit of integration because the approach of each is to transform the much more flexible network structure into a more restrictive BOM. The few apparent discussions of a combined MRP/network analysis system applied to manufacturing [5,6] have not been explicit enough, nor detailed and implemented to an appropriate extent.

In this paper, the conceptual framework of such a system is described, one that provides coverage for the entire make-to-order contract cycle, including pre- and post-manufacturing activities. The similarities and differences between MRP and Network Analysis are outlined and the relative strengths and weaknesses of each are also discussed. Finally, the application of such a model in the manufacture of customized compressors is reviewed together with some promising results that are also presented.

2. The Structures of MRP and Network Analysis

The fundamental structure of both MRP and Network Analysis is a combination of static and dynamic elements. Within MRP, the static element is the BOM, or the end product explosion into its assemblies and component parts, which serves to answer the question "what is to be made." The dynamic component of MRP includes the backward time analysis and provision of resources through inventory control, purchase orders and work orders. The dynamic component answers "when" and "how" to undertake the individual tasks required in order to achieve the fulfillment of the overall business plan.

Similarly, network analysis is comprised of static and dynamic components. The static component is the geometry of the project network, which depicts "what" is to be done. The dynamic component consists both the two-way time analysis and resource allocating/scheduling, which, like the dynamic component of MRP, determines when and how to proceed to best meet the goals of the project.

Given the fundamental similarities in the constitution of the two systems, the feasibility of combining the features of each into a single system becomes clear.

2.1 Material Requirements Planning(MRP)

The success of an MRP system is largely dependent on a properly constructed Bill of Materials, which defines the product structure. But within the structure of the Bill of Materials lie several weaknesses that limit the application of MRP to make-to-order environment. A Bill of Materials is a hierarchical structure defining and relating the components of each assembly and subassembly of a product[7]. The links indicate a sense of

belonging, i.e., a parent-child relationship; components at a given level in the BOM "belong" to their respective parents in the next higher level. Such notation depicts the assembly of components and raw materials into higher level assemblies or subassemblies.

Each element in a BOM represents a physical material or component. The activities necessary to create each element, such as purchasing, assembling or machining, are implied by the links between elements and their "children." The time required to perform the activity is reflected in the lead time given to that element. Thus a BOM element always has a material content associated with it and will generally have an implicit work content as well.

In a make-to-order environment, there are usually many important activities not directly associated with the assembly or the processing of a specific item, i.e., activities with work content, but no material content. Such activities often occur in pre- and post-manufacturing phases of a contract and may include marketing, estimating, engineering, production control, erection, and commissioning. In fact, manufacturing activities may represent only a small portion of the entire contract cycle in some industries. Hence, by using MRP alone a substantial portion of the contract content cannot be represented in the BOM, and therefore cannot be controlled.

A second weakness in a BOM structure is its hierarchical format. A typical BOM is pyramidal in shape with explosions allowed only downward; an element may have more than one component, or child, but no elements can have more than one parent (unless duplicates of the element appear in other locations in the same BOM). A practical application in which multiple parents are required is in the event that components are temporarily assembled for testing before

final machining or other finishing processes can be applied. After testing, the assembly is disassembled and the individual parts completed before final assembly. Attempting to enter the indicated relationship into an MRP system would either result in an immediate error, or, if not caught by the system checks, the MRP logic would duplicate the requirements for the temporary assembly, since it is the child of two parents.

Another weakness of the BOM structure is the restriction of the links between elements to "finish to start" relationships. An activity cannot start until all those preceding it have been completed. More flexibility would be obtained if it were possible to define relationships between activities which should be allowed to overlap each other and those which must be separated by a time delay or lag. Since make-to-order products are typically highly sophisticated and involve large numbers of components and activities, this added flexibility is certainly desirable.

The timing process of MRP similarly has its shortcomings. The major deficiency is the lack of a two way time analysis during scheduling. MRP logic begins with the due date of the end product, and works downward through the BOM structure, using the lead times of each element to assign due dates for each. The resulting time schedule is comprised of the latest dates at which each component or assembly must be available and ready for use in the next higher level of the BOM. This approach is dictated by the ultimate objective of MRP which is to minimize the time that inventory and work in process items are present. If however, there is any delay such that any of these components or assemblies is not available until after its scheduled date, the end product will be delayed as well. This is something encountered in practice very fre-

quently and the result is a number of costly rescheduling iterations aiming to reduce the length on subsequent work items to make up for some of the delays. Using the terms of project scheduling, all elements in an MRP BOM are scheduled as critical activities. No attempt is made to determine the amount of extra time, or slack, that may be available to some of the components/assemblies without affecting the overall project schedule. Given the length of time and number of components/activities involved in a typical make-to-order product, this approach is obviously not practical.

One of the biggest strengths of MRP which is desired and fully applicable to a make-to-order environment is the integration of scheduling, inventory control, and purchasing functions. As MRP explodes the BOM to perform scheduling, it also checks inventory records and pending orders for the components, raw materials and purchased items required to complete each element. Gross requirements are compared with quantities on hand or on order to produce the net requirements to meet the production schedule. For purchased materials and components, the purchasing department is alerted so that these materials may be ordered at the proper time. These functions are highly desirable in the combined MRP/Network Analysis system, if it^{is} to be applied in manufacturing.

2.2 Network Analysis

The two most popular forms of Network Analysis, CPM and PERT, developed in the late 1950's and early 1960's were designed to aid in the planning, scheduling and control of large scale projects. Both are centered around the "project structure," represented by the project network of tasks which depicts the activities involved and how they depend on each other in terms of sequence and inter-relationship. Two basic network structures are commonly used, acti-

vity on arrow and activity on node. The latter, also known as the precedence network, was developed in the early 1960's and is perhaps the most flexible structure and therefore the most applicable to a make-to-order environment. In a precedence network, activities or work items are placed in boxes and linked by dependence lines which define the logical predecessors and successors of each. Further, precedence networks allow for the linking of activities whose start and finishes are not coincident with the starts and finishes of their immediate predecessors and successors; activities may overlap each other, or may be separated by a lag, i.e., a time delay. Figure 1 displays the three different types of relationships available in precedence networks [2]; a fourth type of relationship, "start to finish," is equivalent to a "finish to start" arrangement if the two related activities are put in reverse order.

Unlike an element in a BOM, an activity in a precedence network may have as many predecessors and successors as necessary, thus removing the BOM pyramidal constraint. Each activity must have a work content, and may have a material content, a resource content and a cost content as well. A precedence network can therefore be used to represent the entire spectrum of activities for a contract. One final advantage of the precedence network is that it lends itself to the identification of each work item by project, or contract number. This is a useful feature given the customization required in a make-to-order environment. For these reasons, the precedence network structure is clearly superior to the traditional BOM structure in a make-to-order environment.

The scheduling, or dynamic element of Network Analysis, is also superior to that of MRP. In addition to performing a backward time analysis, which

results in the latest possible dates for each activity, Network Analysis also involves a forward time pass, which begins at the start of the network and produces the earliest dates at which each activity is allowed to start, subject to logistical constraints (eg availability of resources) and the completion of preceding activities. With both "early" and "late" dates for each activity, it is possible to determine the amount of slack time available to each activity. The total slack time, or total float, for each activity is calculated as the late finish date minus the early start date minus the duration of the activity. If the starting date of an activity is delayed, the overall project is not affected as long as the activity is started by the late starting date. Total float may belong to an individual activity or may be shared among several activities on the same path. The free float for an activity, if present, can be used without affecting any other activities.

In any project there will be one or more longest (i.e. critical) paths through the network diagram, comprised of critical activities. Any delay in the start of a critical activity will delay the completion of the project, unless future activities can be shortened to compensate for the delay. Knowing which activities are critical and which are not allows for the best use of resources so that the project can be completed as planned.

Network Analysis also provides several tools for the dynamic control of projects. Using the early and late planning dates generated by the two way time analysis, a bar chart can be created, graphically depicting the planned times and available float for each activity. Resource aggregation and scheduling are also facilitated; by comparing the resources required during the course of a project to those available, one can modify the planned dates by

generating fixed scheduled dates that are realistic with regard to resource utilization. To minimize the effect on the overall project, scheduling takes advantage of floats wherever possible. The effect of extending an activity beyond its float to adjust the resource requirements is immediately indicated. Cash can be treated as a storable resource, such that the schedule can be adjusted to reduce the cost of capital during the project. These capabilities are not available in MRP where schedules once generated are stiff; a bar chart can still be produced without, however, any slack time on activities. Resource requirements are inflexible as well. Hence, Network Analysis provides a much more realistic schedule.

3. The Combined MRP/Network Analysis System

Given the fundamental similarities between MRP and Network Analysis, it is somewhat surprising that manufacturing systems designers have not combined the features of each into a single system. This section is intended to illustrate the concepts of the integrated system.

To illustrate the commonality of the "topology" or "geometry" which identifies the static element of a Manufacturing and a Network Analysis system, let us consider the hypothetical manufacturing Bill of Material structure in Figure 2a which is also shown in precedence network form in Figure 2b. The product family-tree links which indicate that component items belong to their parent assembly can be seen as logical precedence links, indicating that an assembly is dependent on the availability of its components. Furthermore, the content of each box is slightly different between the two diagrams. In the BOM drawing the box marked with "Comp 1" merely depicts a part which is required to form the assembly A. In the network drawing the equivalent box,

possibly identified by the same part number, takes another dimension which is to indicate the action of issuing this item to manufacture prior to it being assembled or otherwise processed. Thus, the network activity marked "Comp 1" is much more comprehensive, as it encompasses an element of action, apart from merely accommodating a material content in it.

Similarly, component 8 is a machined part in the Bill of Material, while in the network, the activity marked as "Comp 8" also encompasses the machining operation(s) required to change the part status from a casting to a finished part. The activity "Comp 8" has a duration equal to the machining operation time(s) plus any set-up, movement and queuing times involved in the particular machining function. It also has a resource content and a cash flow requirement.

Finally, assemblies and subassemblies in a precedence network can be seen as the action of grouping the individual parts together, in addition to the mere material content as implied in a product structure.

Concentrating now on the logical links between component parts and their parent assemblies, these can be seen as typical relationship lines between activities, indicating that an assembly cannot be formed until all of its components are made available, and if necessary, machined (eg., subassembly E, Figure 2b.).

Once the fundamental geometrical similarities between BOM and network analysis are established, one can now enlarge the scope of Bill of Materials by encompassing a number of additional tasks, even without any material content, but with a definite work content, which are inherent in a manufacturing process. The way that MRP systems have been designed does not allow for incorporating such "non-material" elements. In Figure 3 for instance, an extra

activity has been added, marked as "subassy D test," which indicates that an in-process test is required prior to proceeding to final machining of its components and final assembly work. A typical example is a compressor cylinder which is temporarily assembled and tested before it is finally machined and assembled. It must also be emphasized that traditional manufacturing systems do not allow the situation where an activity (eg., Subassy D Test) is the child of two higher level elements. In such a case there would be an inconsistency in the system caused by the fact that two different items, 2 and 3a are made of the same "component D," in addition to the fact that MRP would create a dependent requirement for two D items when exploding the BOM structure.

Apart from the ability to explode parts "upwards" and to introduce non-material tasks, a network-type-product structure allows for the employment of a variety of relationships between work items, such as those illustrated in Figure 1. Thus if a component is not needed immediately at the beginning of an assembly operation, it can be linked to its parent assembly with a finish to finish relationship together with some lag (eg., "Comp 5-Motor" and "Assy B" in Figure 3). This extra flexibility has a beneficial impact on work in progress which can be substantially reduced.

The overall effect of all these additional possibilities offered by a precedence network diagram into which a typical product structure can be converted, is that a much more realistic and comprehensive flow chart of activities and tasks can be produced. This in turn lends itself to a number of other useful functions: resource aggregation and leveling, cash flow projections, cost calculations, simulation of hypothetical conditions by tem-

porarily altering the logic and/or the contents of a product network and finally collection of historical and statistical results.

The extension of the proposed techniques so as to incorporate other functions of the production cycle of contracts is limited only by the extent of one's imagination. Customer interfaces, such as drawing approvals, staged payments and witnessed tests, subcontractors' activities, vendors' progress, commercial interfaces (eg., insurance coverage, bank involvement, lawyers' consultancies, etc.) and shipment arrangements are the most common activities interfering within a manufacturing cycle.

Moreover, the network Bill of Material diagram can be extrapolated at both ends to take into account pre-manufacturing and post-shipment activities. Marketing, estimating, engineering and production control can be incorporated in the plan so that their activities can be scheduled and their performance checked against plans. Erection and commissioning activities and materials can be displayed at the other end of the "networked" bill, thus accomplishing the full production cycle of any contract.

The idea of such an extended Bill of Material structure can be illustrated in conceptual form, as in Figure 4. It may be called a "Hyper Bill of Material" for a contract.

A forward and backward time analysis will produce the early and late planned dates for each activity in the Hyper Bill of Material. Resource allocation and scheduling, performed in conjunction with other existing contracts, will then produce the fixed scheduled dates for this particular contract. These scheduled dates of manufacturing activities will be fed into the MRP logic for the generation of the necessary purchase and work orders as

described in more detail in the following section.

This approach differs from that taken by Aquilano and Smith [1,9] in integrating Critical Path Method and MRP for project work. Instead of using Network Analysis concepts as the driver of the CPM-MRP system, the conventional project network is transformed into a traditional Bill of Material structure, with its reduced flexibility. Activities that must have more than one parent (eg. labor) must be duplicated as many times as required and each copy linked to a single parent. All but the simplest of project networks are thus likely to be greatly enlarged when transformed into this format. Furthermore, the logical links between children and their parents are limited to finish to start, which is likewise restrictive for many projects. The result of these constraints is bound to make the monitoring and control of the project more difficult.

The product structure of Aquilano and Smith does allow non-material elements and the scheduling algorithm ensures that an activity appearing more than once in the network is only scheduled a single time. An interesting feature of the algorithm is that resource constraints and availability can be considered during the scheduling process, providing a schedule tailored to the current resource inventories (storable resources) and expected availabilities (non-storable resources). In a make-to-order environment, however, these features are generally not necessary. Storable resources for such products usually fall into two categories: those commonly available, small, standard components that are kept of hand at a minimum stock level and those that are customized or otherwise too expensive to maintain in stock, hence only ordered when needed. The proposed approach suggests that in the first case no special

consideration is required of the system and in the second the ordering of parts is controlled by the MRP logic but not the MRP timing. Procurement leadtimes are already identified in the network.

As for non-storable resources, the labor and equipment can be adequately scheduled by the network analysis techniques of resource aggregation and leveling, which will determine the effect of resource availabilities on the schedule well before manufacture begins. With these capabilities, it is possible to answer "what if" questions to determine the optimum quantity of resources to obtain (if necessary) and have available on a given project.

4. The Conceptual Design of the Proposed System

The conceptual design, sometimes referred to as feasibility study, consists of the specification of the principal subsystems, the arrangement of and the relationships between these subsystems and their components, the general nature of the inputs and outputs and the expected performance of the entire model. The general system layout is provided in Figure 5.

The Order Entry serves as the feeder of customer orders to the system, as seen in Figure 5. It determines the final products to be engineered and manufactured and the delivery due dates. The Bills of Materials constructed as the result of the design effort translate these requirements into materials and work contents appropriately structured, encompassing also all of the non-manufacturing tasks to be carried out during the pre- and post- production cycles. The Scheduling module determines the early, late and scheduled dates of each task, resulted from the time analysis and resource leveling processes. MRP whose timing function is bypassed by the scheduling module uses the scheduled dates of all material related tasks and generates the necessary purchas-

ing and manufacturing orders to satisfy the end product requirements. Inventory Control is used to merely handle a few commonly used class C items which are kept in stock regardless of the actual backlog of customer orders. Nevertheless these stocks are still considered by MRP before raising any purchasing or manufacturing requisitions. The execution of procurement and shop orders is left to the Purchasing and Shop Floor Control modules of the system. Finally, the Contract Costing module is there to capture and maintain budget and actual cost elements associated with each task by contract.

Some substantial issues related to the function and the performance of the system's modules are presented in the following sections.

4.1 Order Entry

At the pre-award stage the Order Entry can be used to generate a potential order to the system by creating a "skeleton costed BOM" which encompasses the major assemblies of the end product. This can be facilitated by using one or more existing modular standard BOMs, from which selected options are copied under a tentative customer order number. This skeleton BOM converted to a precedence network may subsequently be enlarged by introducing some major Engineering, Estimating and Purchasing activities to cater for the pre-manufacturing work load. Additionally, some customer interfaces and sub-contractors' work may further expand the network for it to take the form of a contractual "Hyper-BOM" as defined earlier. A priority code assigned to the potential contract will allow for resource allocation in conjunction with the existing work load, achieved by a tentative run of the Scheduling Module. Thus, delivery dates and new resource and cash flow profiles can be obtained and used by Marketing while negotiating with the potential customer.

After the confirmation of the customer order the provisional order entry to the BOM and Scheduling modules can be firmed. The contract number, delivery date, contract value, terms of payment and customer details can be fixed, thus generating a new contract in the system.

4.2 The BOM and Scheduling Modules

The core of the proposed system is the combination of these two modules. They form a system which encompasses both fundamental elements common to any action plan: the static and the dynamic. The first indicates "what" is to be done in a form of charts of logically interrelated tasks and the second suggests "when" and "how" it is best to execute these individual tasks, leading to the accomplishment of the entire plan. As suggested previously the static element represents the "geometry" of the system which identifies material and work input needed to execute contracts as opposed to the dynamic element which introduces the dimension of time as an essential parameter to create schedules out of plans.

Both at the tendering stage of a new contract and the pre-manufacturing stage of a firm contract, selected standard BOM structures are copied under a contract number (either provisional or firm) within the BOM module. Hence a transaction must be provided to perform copying of customized BOMs by entering the contract number and the unit number within the contract. In addition the part number of the end product must be provided so that all assemblies, subassemblies and component parts will follow their top "parent". All assembly-to-component dependencies must be translated to activity precedence dependencies of the type finish (of component)-to-start (of assembly), until they are modified later to more flexible dependencies.

The functional operation of the Scheduling module is based on the principles of the Critical Path Method and more specifically on precedence network analysis as explained before. All features of this method, namely time analysis, resource allocation and leveling and cost buildup, are extensively used in a multi-contract and multi-resource environment.

The nature of activity content in a CPM system is not restricted by any rules apart from the need to assign a distinct work content and duration to every work item. Thus, both "material" and "non-material" types of activities, in the context discussed in section 2.2, can be accommodated.

The time analysis based on a forward and backward pass over the network of activities provides the earliest and latest dates for each task to be performed, thus producing a more flexible plan than that of a pure MRP system. If available resources are compared to the resource demand and attempted to satisfy it in the best possible way, a more firm schedule is computed, which if not met will result in resource under- and/or over-utilization. These discrepancies can be measured as suggested in previous work [4] before unnecessary iterations are executed. However, contracts will not necessarily become overdue provided that delays have not exceeded the remaining float of activities, i.e., the difference between latest finish and scheduled finish. This feature makes CPM superior to MRP in which any delay is bound to cause inevitable expediting for the remaining tasks.

Finally, the ability of CPM to allocate cost elements on activities and to subsequently produce reports on cash expenditure versus time is another useful feature which is used for monitoring cash in and out-flow on contracts, both individually and cumulatively. A typical cash flow curve for a given contract or group of contracts is shown in Figure 6.

4.3 The Execution Modules

All due dates for purchasing and work orders are fed into MRP as soon as they are released from the scheduling module. MRP then raises firm planned orders with dates as dictated by scheduling and quantities as calculated by the BOM and Inventory Control modules. The flow of data, therefore, from scheduling towards the manufacturing cycle is established via the MRP module. The feedback from the manufacturing system to scheduling is originated by and transmitted from the Inventory Control, Contract Costing and Order Entry modules.

Outside the manufacturing area, data communication to and from the Scheduling module can be performed directly by the users on line. Task lists and graphs can be created and distributed to all parties involved and progress is monitored by departmental managers under the supervision of Project Management and Production Control. Progress updates are entered into the system by authorized users from lists of accomplished or semi-finished tasks.

Apart from grouping orders MRP should be capable of recognizing multiple occurrences of parts within the same customized BOM and split orders if their period of supply exceeds the predetermined time horizon.

MRP interfaces with other system modules on a number of occasions:

- Interface with the Scheduling module to obtain requirements related to contractual needs.
- Interface with Purchasing/Receiving to transmit purchase requisitions and Shop Floor Control to transmit manufacturing requisitions. A feedback from these modules must be established to enable MRP to identify completed as well as overdue orders.

- Transfers of parts from one contract to another recording by Inventory Control, must be signalled to scheduling which reschedules for replacements to be ordered by MRP.
- Rework on or replacements for scrapped items is requested through the Shop Floor Control and Inventory Control modules to scheduling in order to reschedule the respective manufacturing or purchasing activities and to cause MRP replanning the appropriate orders.

Finally, a list of unsatisfied orders must be produced by MRP at the end of every contract's manufacturing cycle, to be handed to the Customer Services division, or to the customer, before any erection work can start.

The Purchasing/Receiving module must be designed to aid in timely acquisition of purchase assemblies, components and raw materials for the end item demand identified in the Order Entry, according to the schedules generated already. MRP plans for the release of requisitions at the due time to meet schedules and the Purchasing/Receiving module changes requisitions to purchase orders and monitors them from the time they are released until receipt of the goods from vendors.

The Inventory Control module must be designed to capture information about all Stores events and to monitor the location and quantity of each part in the system. The data maintained by Inventory Control is critical to the success of the entire system. MRP depends on accurate inventory records for planning, purchasing and works orders for stock items. Contractural parts must be monitored by contract and unit number in addition to part numbers but they should never be kept in stock.

The Shop Floor Control module must be designed to monitor and record manu-

facturing activities on the shop floor and to aid in utilizing work centers and labor efficiently. The constituents of the Shop Floor Control module are data related to work centers, job routings and labor force, as in a typical MRP system. Jobs, however, should be tracked by contract number.

The most important feature of the Contract Costing module must be the ability to track costs by contract as well as by product. Standard product structures must be costed to provide the basis for cost estimates and tenders for potential contracts. This costing function is performed by product type in its general context which encompasses many product options and alternatives. Customized product structures must be costed accurately to reflect budget and actual cost of every particular customized product configuration.

Costing must be based primarily on costing material and labor content of the static element of the manufacturing system housed in the BOM product structure of the end product.

5. Case Study

Ingersoll Rand is a world wide recognized compressor and pump manufacturer with plants in more than seventeen countries and a sales volume exceeding \$4 billion annually. Their corporate strategy was to develop and implement sophisticated, on-line production management systems, using common data throughout the corporation.

In the United Kingdom, the Whythenshawe plant of Ingersoll Rand, dealing exclusively with custom made reciprocating and turbo compressors, decided to investigate the possibilities of acquiring a turnkey system which would cater for the basic requirements of make-to-order manufacture. The most fundamental ones include:

- Contract-tracking capability throughout the system, via multi-level pegging to the top level part.
- Capacity planning and efficient scheduling of resources.
- Costing and progress tracking by contract.
- Design change control by contract rather than date or lot number.

The first author was a member of the system development and implementation team from 1982 until 1984. It was soon realized that no system off-the-shelf could satisfy these requirements and that only a combination of tools would perhaps meet the basic needs of the business. After extensive search in the market, both in the UK and the USA, CIMS from Cullinet was selected as the most appropriate MRPII system to be coupled with the Application System, a project management (critical path method) package marketed by IBM UK Ltd.

As soon as the Wythenshawe management approved the feasibility study of the proposed system the team started working toward preparing data from two real contracts in order to simulate the functioning of the combined system and further justify the validity of the model. The first step was to amend the item master data programs for component parts so that the latter could take the form of activities with labor, machine time and cost contents. Then the application system was used to manually enter these "activities" and many others related to the non-manufacturing part of the contract life-cycle. The structuring of these activities to form a Hyper-BOM-like network was done within the critical path system which subsequently performed a time analysis, resource scheduling and cash-flow projections.

The two contracts loaded were identified by names rather than contract numbers because the system did not accept numeric entries in the relevant data

field. The names used were SUCO and ANGOLA after the "nicknames" given to these contracts. The results of the time analysis were displayed in a tabular form. Each activity was accompanied by early, late, scheduled and, if applicable, promised (i.e., imposed) dates. Early and late dates were produced as a result of the time analysis of the hyper-BOM of each contract. Scheduled dates were determined after the resource scheduling process which necessitated a few iterations before the highest priority resources were leveled. In addition, a bar chart was drawn for each contract based on the scheduled dates. These dates were subsequently transferred to the CIMS MRP module as firmed planned order dates for further processing downstream in the Purchasing and Shop Floor Control modules. Order quantities for stock items were automatically netted against inventory records to produce net requirements.

Transfer of data between CIMS and the Application System was performed manually because the interfaces illustrated in Figure 5 were not developed yet. Nonetheless, the results were greatly appreciated by the management. The capabilities of the system met most of their requirements which no system alone could satisfy. A sample resource histogram and a cash flow projection graph are illustrated in Figures 7 and 8 respectively.

6. CONCLUSIONS

Given that make-to-order manufacturing lies somewhere between job-shop manufacturing and project work, it seems logical that one could combine the appropriate features from the analytical tools available for these applications into a single system capable of handling the unique requirements in this environment. From network analysis systems one gains the flexible network

structure, which can handle non-material items, allowing for the consideration of activities like testing, inspection and third party interfaces. Direct association of resource and cash requirements to each work item makes provision for subsequent resource scheduling and cash flow projections. Network analysis also offers a large variety of relationships which give extra flexibility in producing contract workflow models. As for time analysis, network systems perform both forward and backward time runs, which reveals much desired floats for most production activities, as opposed to "stiff" schedules generated by MRP.

The conceptual design of an Integrated Production Management System for engineered equipment was presented. The major characteristics of the proposed system can be summarized as follows:

- (a) The conceptual similarities between a CPM and a manufacturing system, i.e., geometry and time analysis, provided the grounds for a combination aiming at managing all of the tasks encountered in a multi-contract, multi-resource environment.
- (b) The entire system is geared to contractual production with the Scheduling module being the time and resource driver of all activities involved from customer's first request to on-site erection and commissioning.
- (c) The Scheduling module is functionally based on the CPM and encompasses all non-manufacturing types of activities within and outside the manufacturing cycle of each contract. Manufacturing activities initially defined by customized BOM structures are also incorporated to the Scheduling module by copying to it and appropriately enhancing

contractual product structures so that the latter assume the form of precedence networks. The resulting network for each contract is a comprehensive definition of work, material, cost and resource requirements, providing the basis for production planning and scheduling.

- (d) The executing modules of the manufacturing system aid in carrying out all of the manufacturing related tasks identified and scheduled within the strategic modules of the system, Scheduling and BOM.

Work towards full integration is currently under way with a workable generic model of the combined MRP/Network Analysis system being developed.

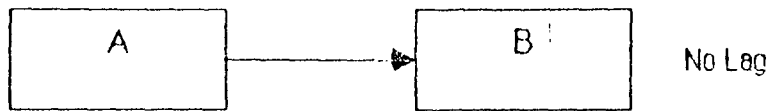
ACKNOWLEDGEMENTS

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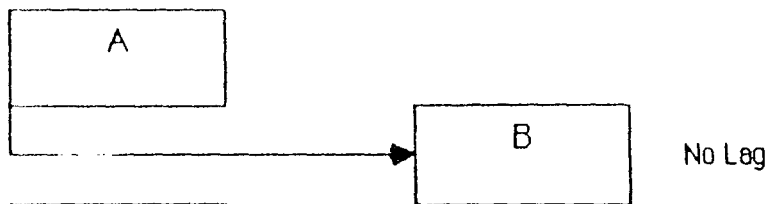
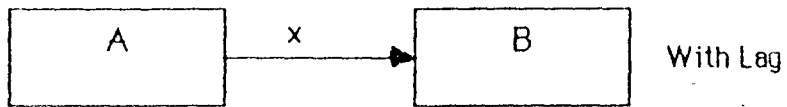
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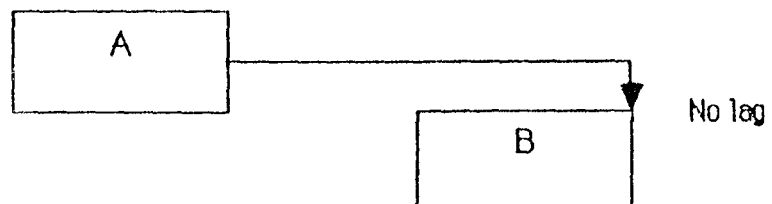
Network Representation



Finish to Start



Start to Start



Finish to Finish



Bar chart Equivalent

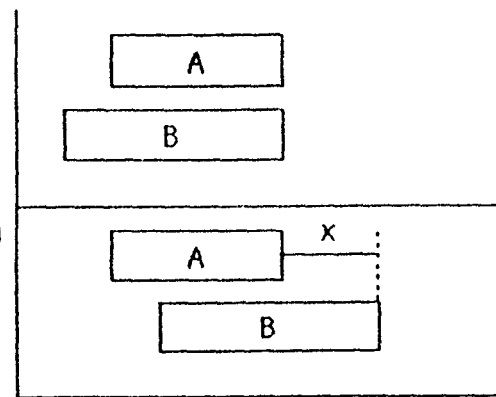
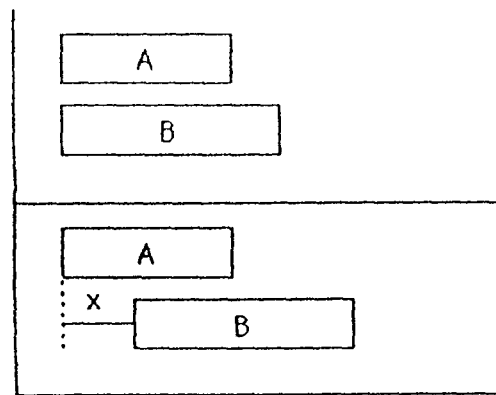
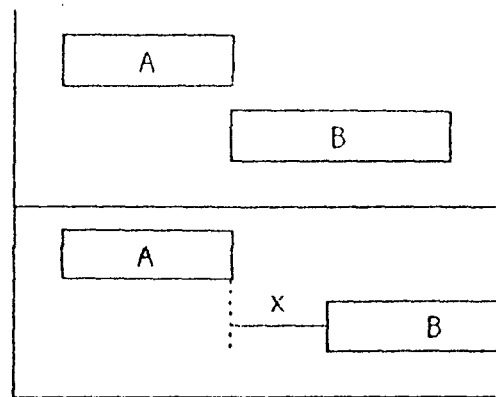
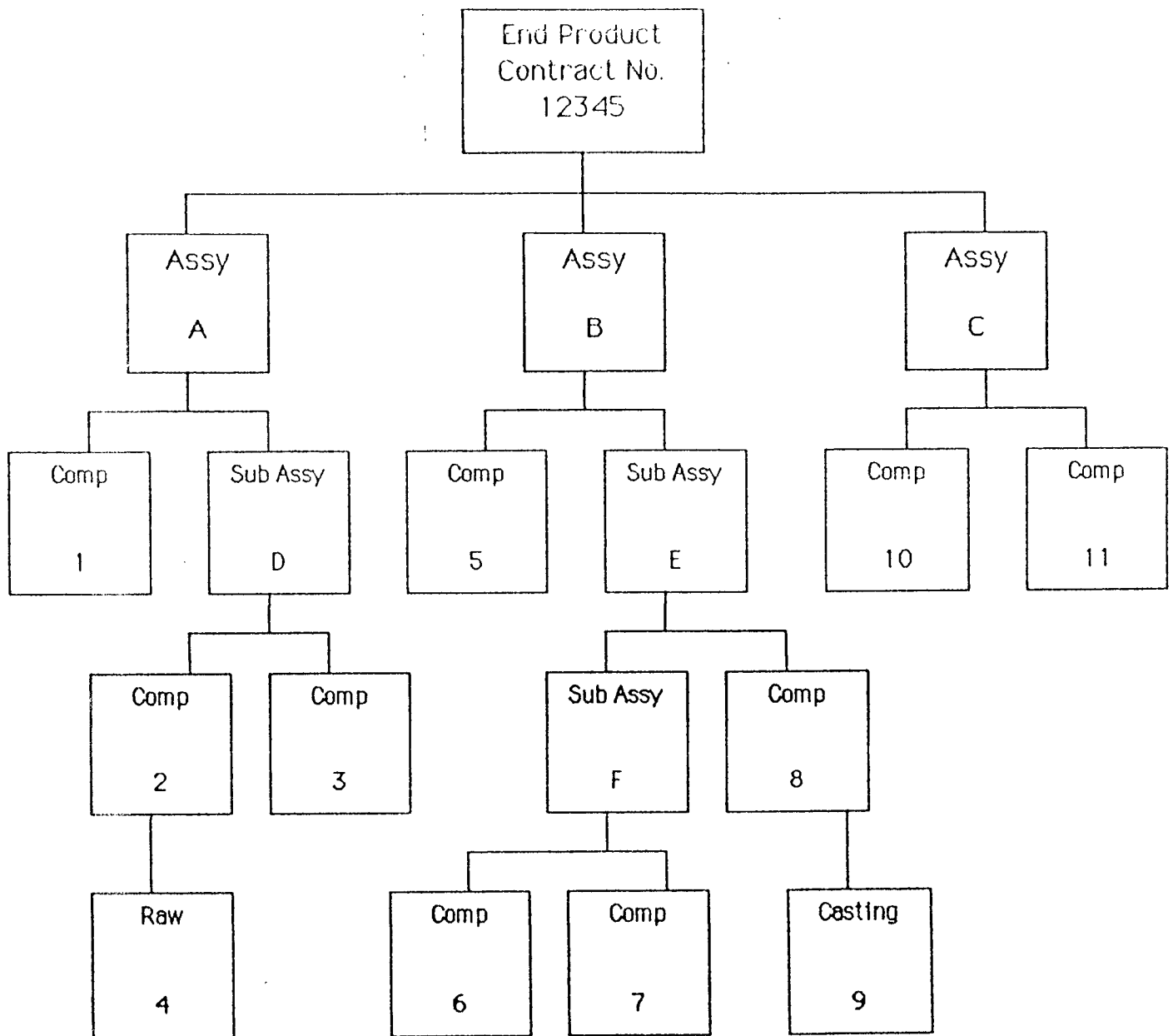
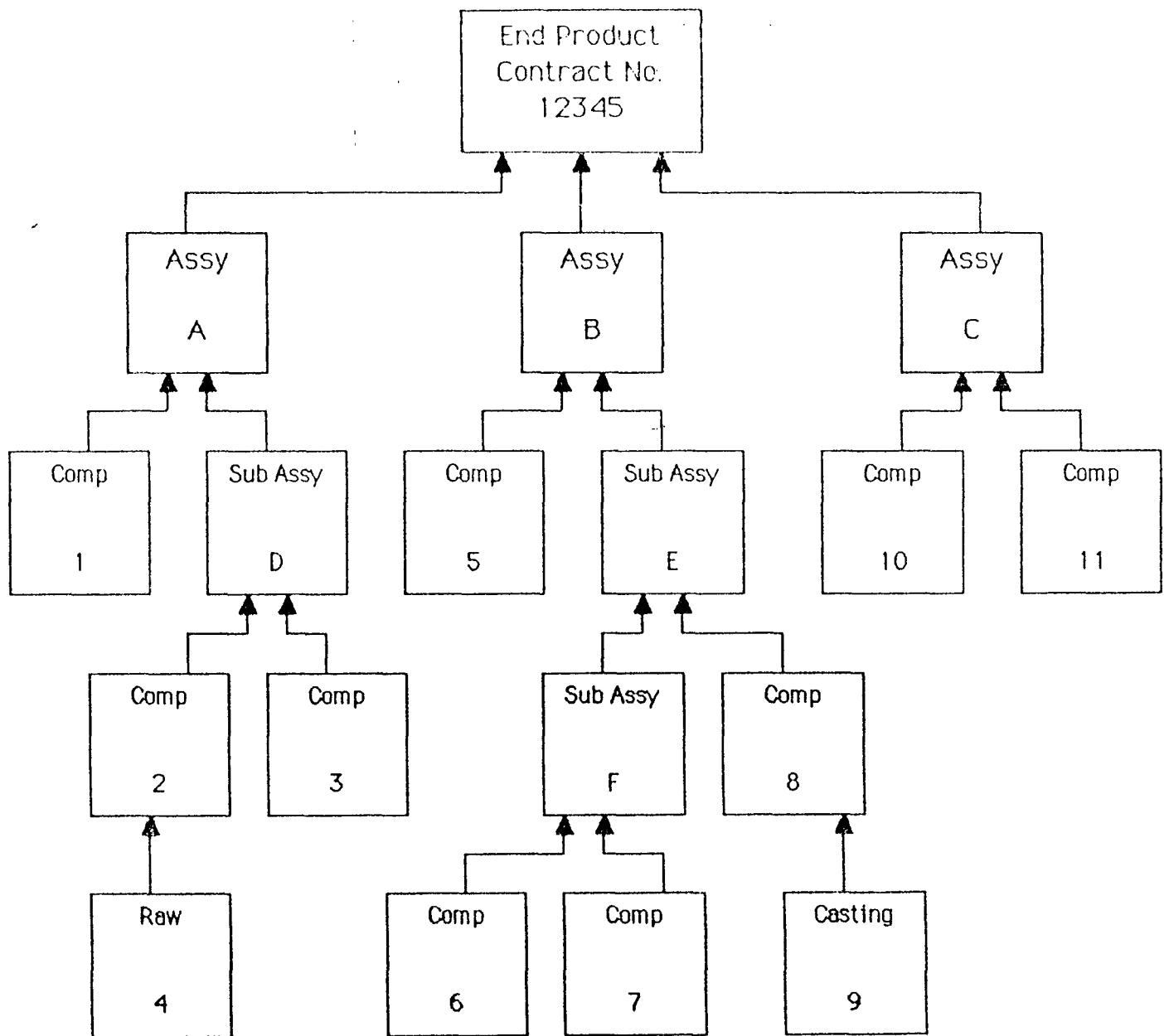


Figure 1. Activity relationships in precedence networks.



(a) A hypothetical manufacturing bill of material family-tree structure

Figure 2a.



(b) The above product structure converted to a precedence network

Figure 2. The principle of topological commonality between MRP and network analysis.

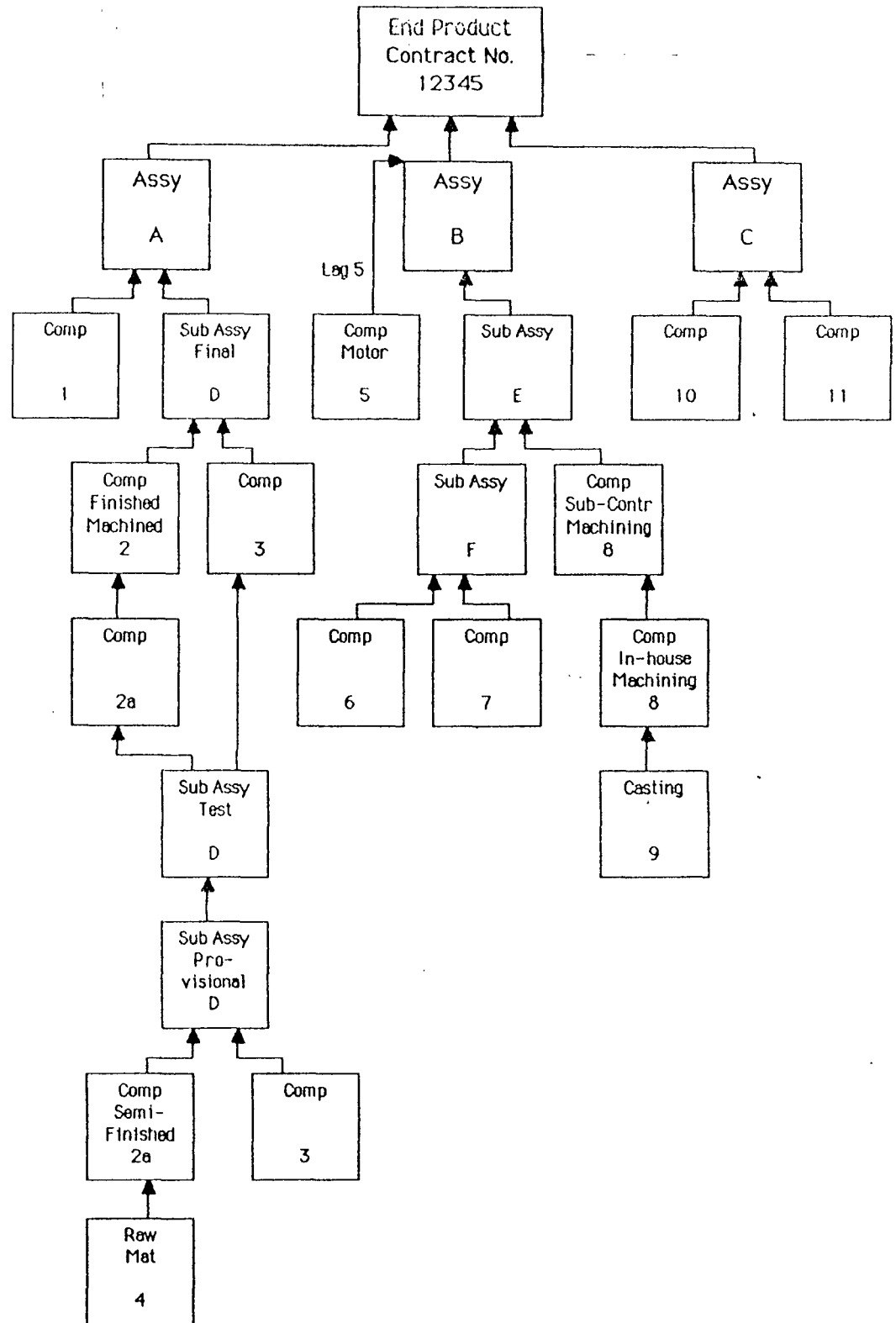


Figure 3. The precedence network drawing shown in Fig. 2(b) enlarged to embrace various other types of manufacturing activities and relationships.

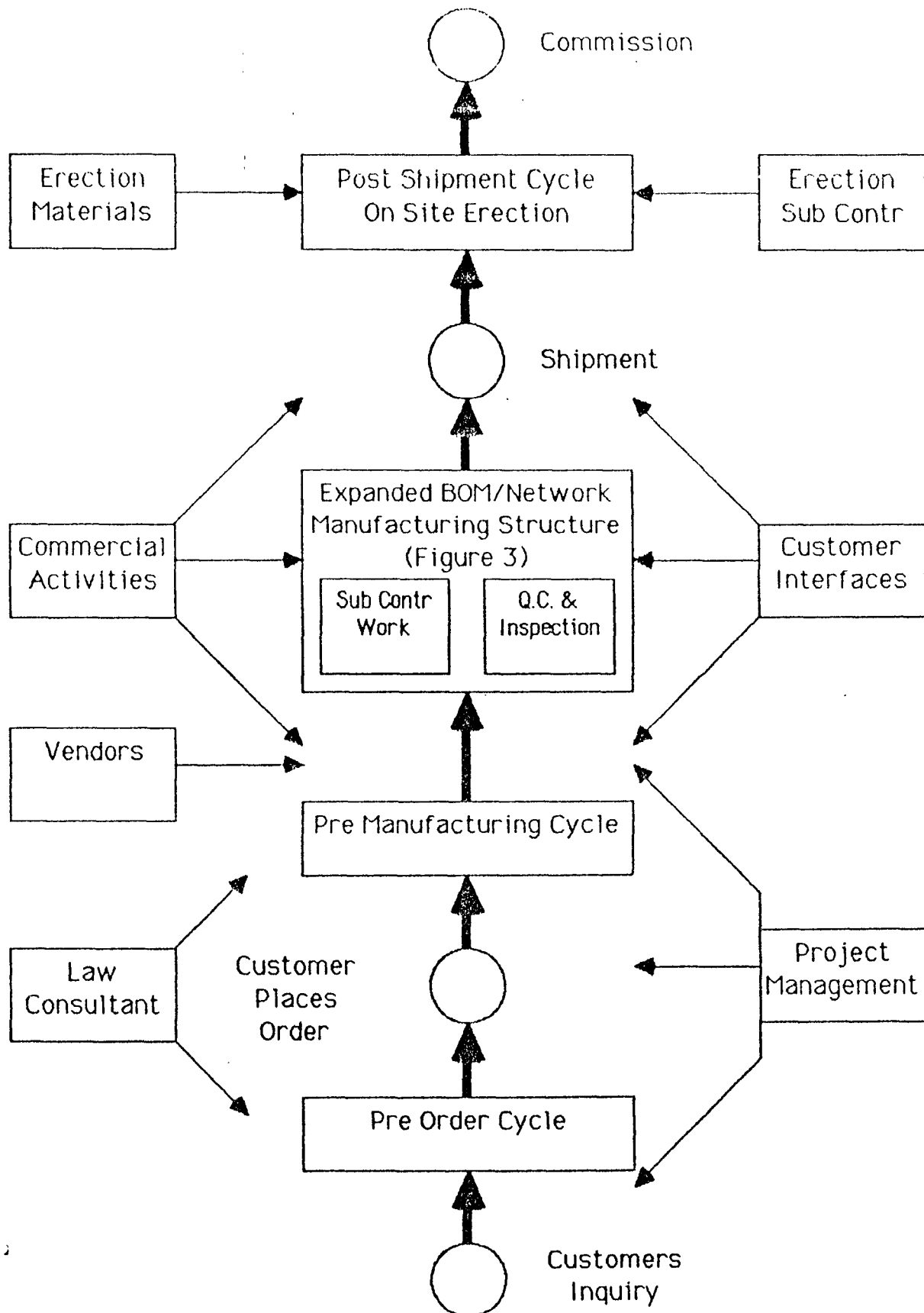


Figure 4. The "Hyper-Bill of Material" concept.

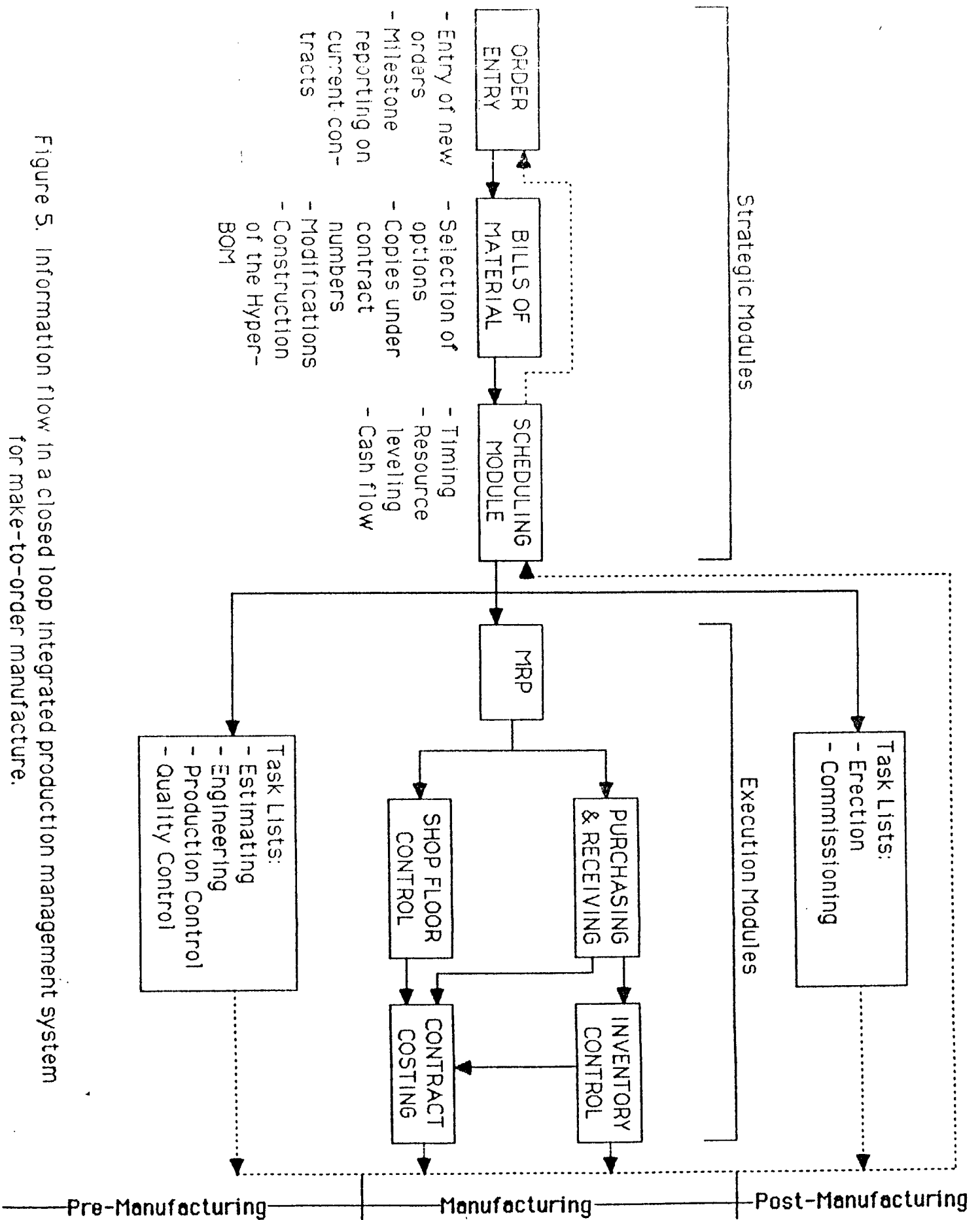


Figure 5. Information flow in a closed loop integrated production management system for make-to-order manufacture.

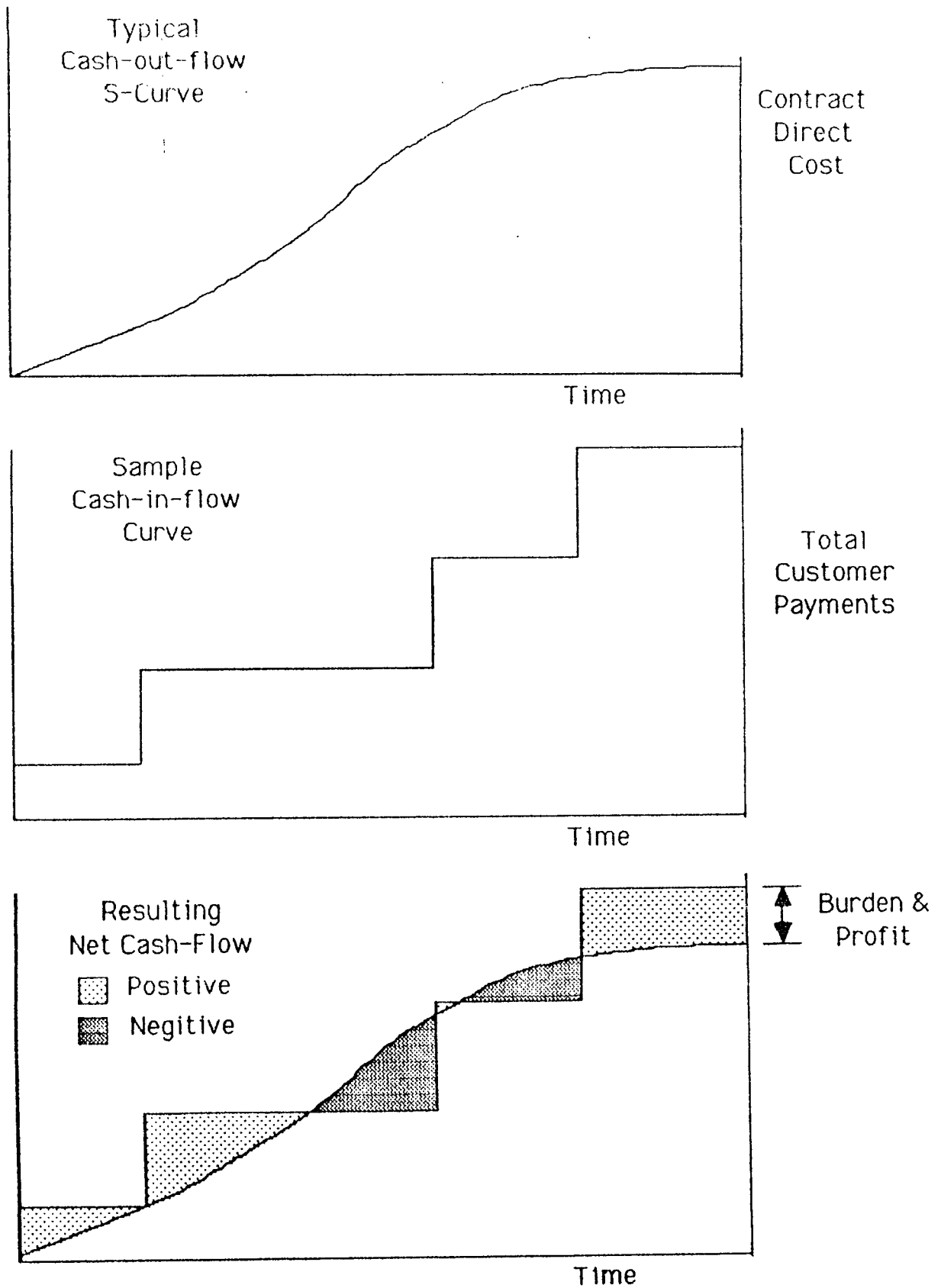


Figure 6. Typical Cash in and out flow curves.

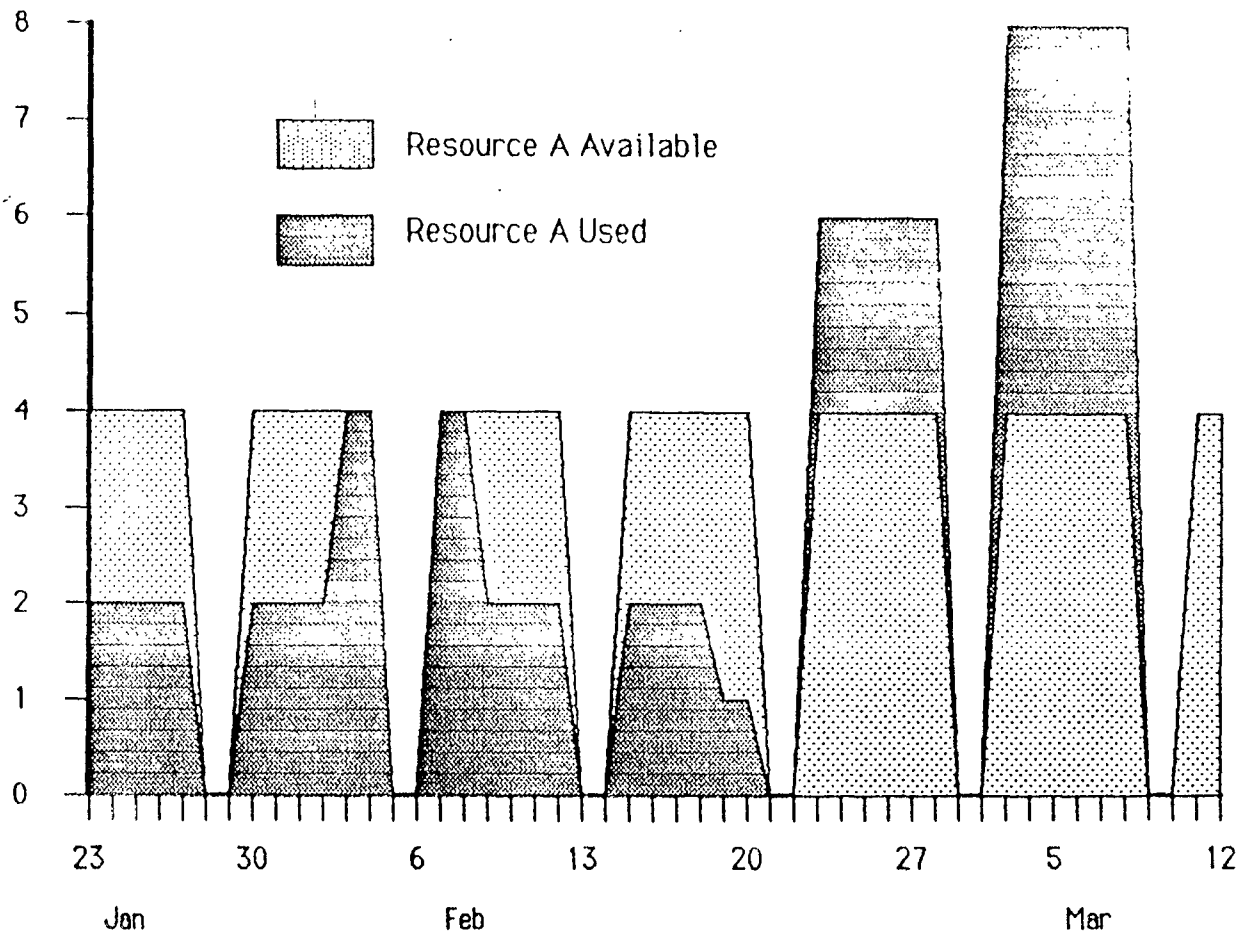


Figure 7. Sample resource histogram from Ingersoll's system.

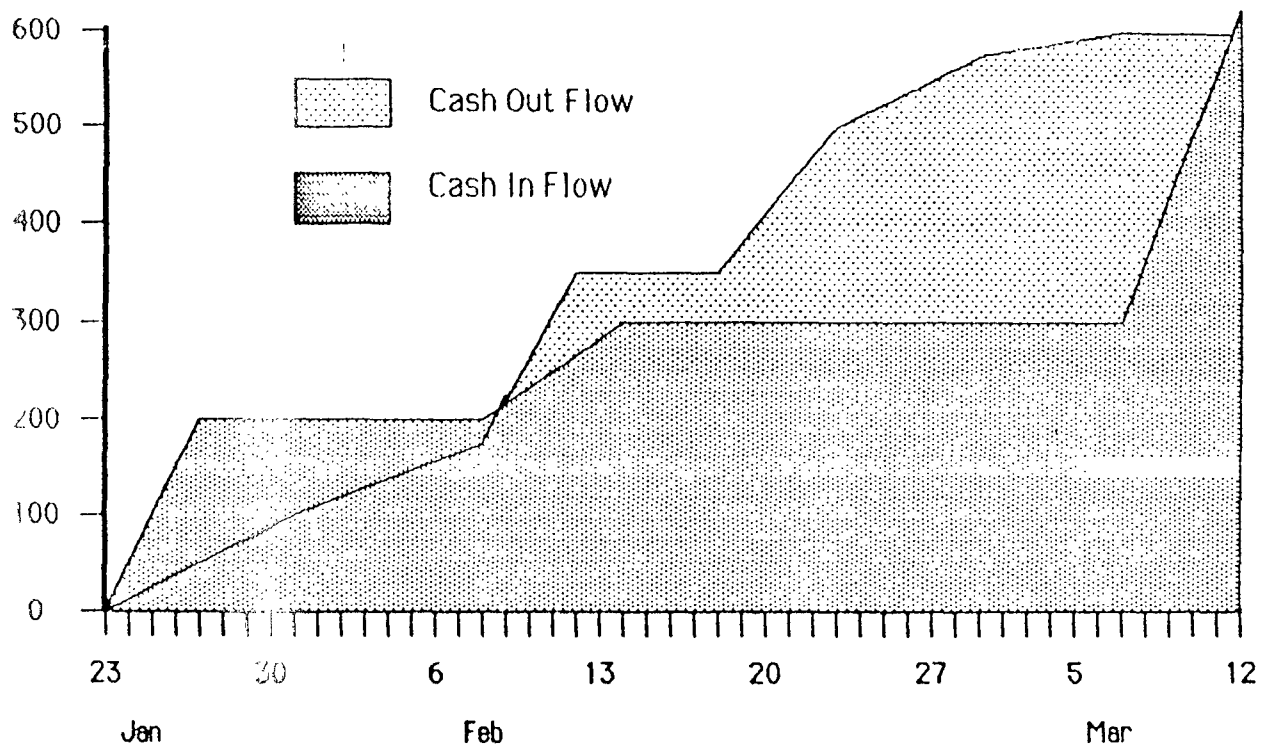


Figure 8. Sample cash-flow projection graph from Ingersoll's system.