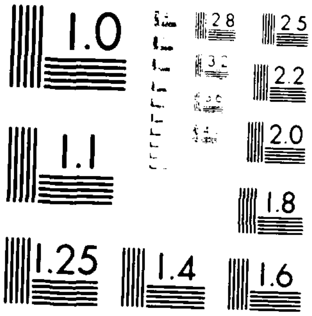
AD-A125 692 THE OUTFIT PLANNING PROBLEM: PRODUCTION PLANNING IN SHIPBUILDING(U) GEORGIA INST OF TECH ATLANTA PRODUCTION AND DISTRIBUTION RESE.. R J GRAVES ET AL. MAR 82 1/1

UNCLASSIFIED PDRC-82-17 N00014-80-K-0709 F/G 5/1 NL

END
DATE
FILMED
4-83
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

12

Georgia Institute of Technology

THE OUTFIT PLANNING PROBLEM:
PRODUCTION PLANNING IN SHIPBUILDING

by

R. J. Graves
L. F. McGinnis

March 1982

PDRC 82-17

PRODUCTION and DISTRIBUTION RESEARCH CENTER

SCHOOL OF INDUSTRIAL
AND SYSTEMS
ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM
OF GEORGIA
ATLANTA, GEORGIA 30332

83 01 20 034

PDRC Report Series
82-17

THE OUTFIT PLANNING PROBLEM:
PRODUCTION PLANNING IN SHIPBUILDING

by

R. J. Graves
L. F. McGinnis

March 1982 PDRC 82-17

This research was supported by contracts DO-A01-78-00-3074 and MA79SAC00067 from the Maritime Administration, Department of Commerce and ONR Research Contract N00014-80-k-0709. Reproduction in whole or in part is permitted for any purpose of the U. S. Government.

THE OUTFIT PLANNING PROBLEM:
PRODUCTION PLANNING IN SHIPBUILDING

Shipbuilding as currently practiced in U.S. commercial shipyards employs little quantitative modelling or analysis in production planning. This paper presents a brief discussion of the shipbuilding process and focusses on one major component which is referred to as <u>outfitting</u>. The outfit planning problem is described in detail and then formally modelled as a generalization of the resource constrained project schedulling problem. The value of the approach as well as barriers to its adoption are also discussed.

1. INTRODUCTION

For a number of years, the U.S. shipbuilding industry as a whole has been recognized as not competitive with the best foreign shipbuilders. Because shipbuilding is considered a vital industry, commercial shipyards therefore receive a substantial subsidy, which is administered by the Maritime Administration (MarAd) of the Department of Commerce. In addition, MarAd supports various research projects through the Shipbuilding Research Program, which are aimed at improving shipbuilding in U.S. shipyards.

In the past, MarAd's research emphasis has been technologically or design oriented, e.g., welding technology, cutting technology, propeller design, hull form design and so forth. More recently, there has been a growing realization that important problems also exist in production methodology, including work methods, production standards, production planning and production control. This paper addresses a particular problem in production planning and control in shipyards, and presents some of the findings of a MarAd sponsored research project.

The problem considered in this paper is called the <u>outfit planning problem</u>. Outfitting refers to the fabrication and installation in a ship of everything that is not considered hull steel, i.e., everything except the hull itself, the decks, and the bulkheads. In many instances, outfitting represents as much as 50% of the cost of the ship and also as much as 50% of the elapsed time for production. Clearly, any improvement in the outfitting process would have a significant impact on the shipbuilding industry.

The primary contributions of this paper are:

1. To describe this important class of production planning problems;
2. To present a formal model of the problem;

3. To examine the impact of shipyard's adopting the solution approach.

1.1 The Shipbuilding Process[1]

Shipyard production activities can be broken into two distinct groups: the steel phase activities, which encompass all the activities associated with fabricating and assembling the hull, up to and including complete ship erection; and the outfit phase activities, which are associated with the acquisition, fabrication and installation in the ship of everything else.

Conceptually at least, the outfit phase activities could all come after the steel phase activities were completed. As a practical matter, of course, this would not be a feasible production method because of the expense of opening up closed compartments to land equipment or to install outfit material such as piping. This extreme oversimplification does, however, capture much of the traditional concept of outfitting as a "successor function" [6]. That is, production often has been treated as two distinct phases with very little interfacing of the steel and outfit activities.

Although various production methods are practiced in U.S. shipyards, the most common method is hull block construction. The ship is divided geographically into components, or blocks. A typical ship might consist of 100 blocks. The steel components of the block are assembled in a block assembly area, and the block perhaps weighing as much as several hundred tons, is then lifted onto the ways for final erection.

Shipbuilding can be viewed in terms of the material flows and primary production facilities. As shown in Figure 1, ship production occurs in three primary facilities with two major categories of supporting facilities

---

[1] Reference [1] provides a good summary of current practices in U.S. shipyards.

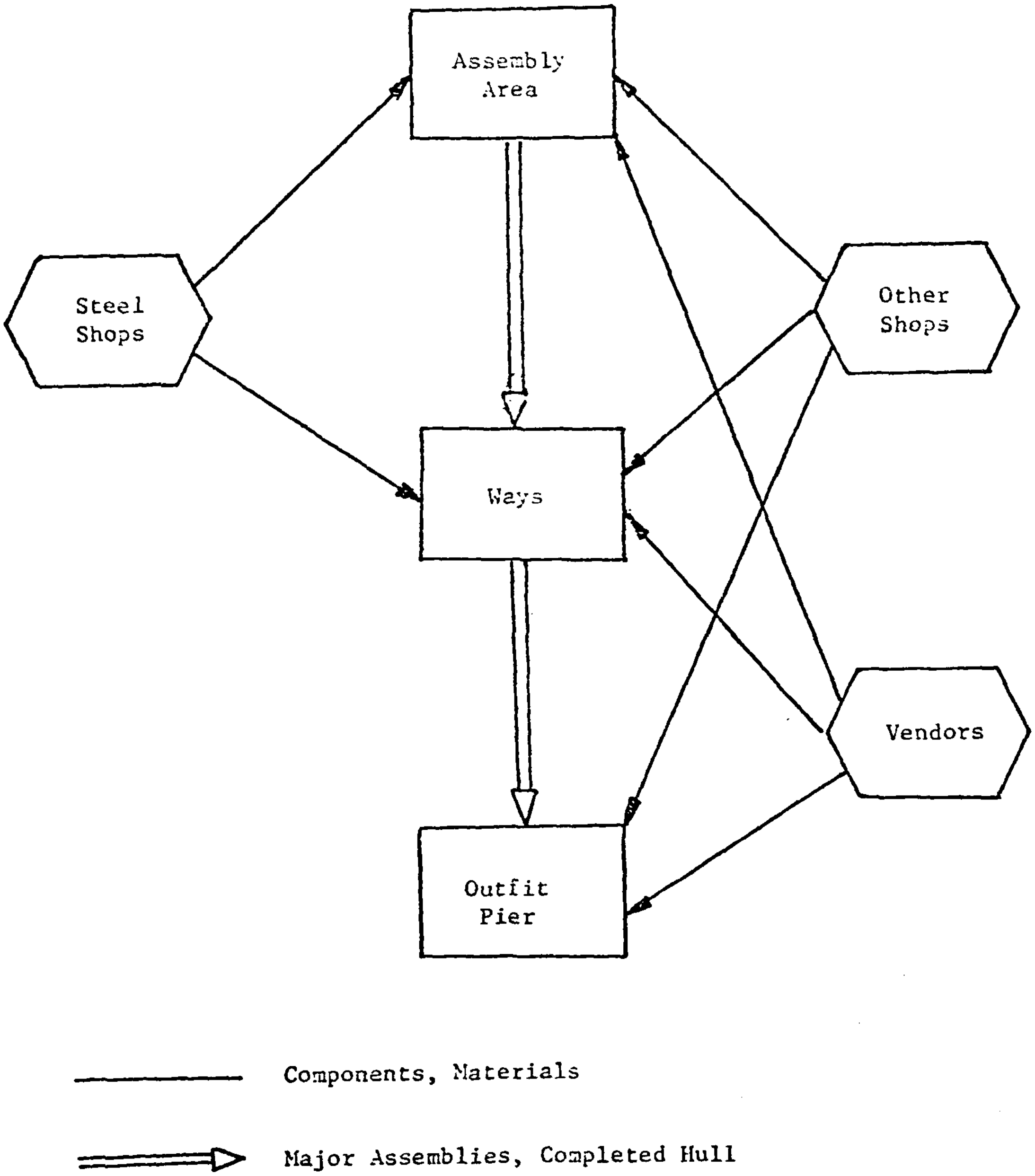


Figure 1. General Production Flow Model

plus outside vendors. The steel shops represent facilities where the steel forming activities take place. This includes welding of stiffeners and bracing to large steel plates. Similarly "other shops" include all the facilities associated with fabricating sheet metal, ducting, wire, piping, equipment, etc.

In this model, the "assembly area" represents any configuration of facilities where steel and/or other materials are brought together and processed prior to actual ship erection, i.e., prior to going on the ways. The ways area is the facility where ship erection, i.e., hull assembly, takes place. After hull assembly, the ship is completed at least to the point of being able to float. The "outfit pier" represents the stage of ship production which follows float-off.

The consideration of facilities and material flows leads naturally to the idea of different production <u>modes</u>:

(1) fabrication: the production of individual pieces of steel, sheet metal, ducting, piping, electrical cable, etc.

(2) assembly: fabricated plates are assembly to form <u>blocks</u>; also individual components may be assembly to form <u>units</u>, e.g., equipment with foundations, valves with piping, etc.

(3) erection: the activity on the ways that results in the completed hull.

(4) outfitting: the remaining production activities that take place once erection is completed.

Steel phase activities cannot be performed after erection, by definition. Outfitting phase activities, however, can be performed in any of the four modes. If they occur before erection, they are preoutfit activities.

Note that the terms "steel phase" and "outfitting phase" have been used to delineate activities by type. The four modes defined above, however, delineate activities by the timing of performance and facilities required. The distinction is an important one since there are options for many activities with regard to production mode.

There are two important aspects to production planning as generally practiced in hull block construction. The first is the work breakdown structure, which determines the definition of the work packages, i.e. the drawings, specifications, operations sheets, work sequences, and material lists defining what to do and how to do it.

The traditional approach to defining outfitting work packages is systems oriented, that is, the various ship systems (ventilation, electrical, communication, hydraulic, etc.) are considered separately. While this orientation follows naturally from the design phase, and simplifies the collection of production cost data by system, it is not the best orientation in terms of production scheduling and control. Only recently has a product oriented work breakdown structure (PWBS) been proposed [9] for U.S. shipyards. In essence, PWBS would yield work packages describing all outfit work required for a particular area in a hull block.

The second important aspect is the structure of the scheduling process. Figure 2 illustrates the relationships between major planning/ scheduling documents and demonstrates both the hierarchical structure of the process and the bifurcation into separate steel and outfit schedules. The dashed lines in Figure 2 indicate that the System Schedule is developed subsequent to and is constrained by the Hull Block Erection Schedule and the more detailed Block Assembly Schedule. This dependence is just one

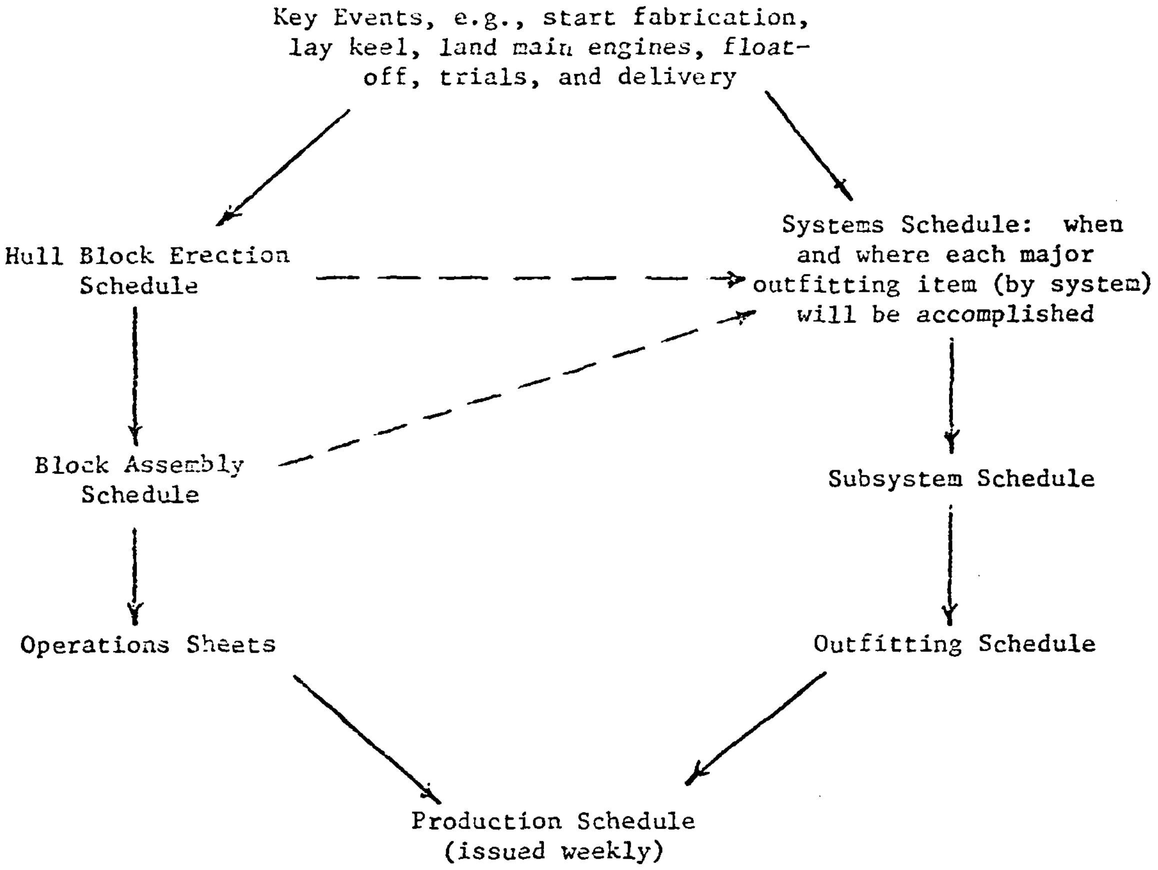


Figure 2. Structure of Production Scheduling

result of the traditional treatment of outfitting as a successor function.

2. THE OUTFIT PLANNING PROBLEM

Current practice in planning and scheduling ship production inherently limits the ability to integrate steel and outfit activities. It results in the bulk of outfitting work being performed in the erected hull, either on the ways, after a block is closed in, or at the wet dock or outfit pier. Working conditions in the hull are not ideal because of factors such as difficult access, limited space in which to work, difficulties in adequately venting noxious fumes, and difficult work positions (e.g., overhead welding). The workplace is typically congested, with high material flow costs, and often hazardous conditions.

It is now widely recognized that many of these problems can be relieved to some degree by doing more outfitting activities earlier in the production process, i.e., either in the assembly area or in the shop (vendor) area. To do this, however, requires a much greater integration of steel and outfit planning than has been the rule.

The fundamental problem is to identify economically desirable opportunities for preoutfitting. This requires answering two types of questions. The first is related to feasibility, i.e., "Is there sufficient time and resource available to do a particular outfitting activity in the assembly or shop area, and is it technically feasible?" The second question is one of economics, "Is it more economical to preoutfit this activity?" What is needed is a systematic way to answer these questions.

Any such evaluation procedure must have two essential components. The first is a flexible work breakdown structure which will identify outfit activities with their geographical location in the ship. The second component is a methodology for selecting the appropriate work breakdown and determining a feasible schedule.

The first component relates chiefly to work methods, while the second relates chiefly to scheduling. The required work breakdown structure has been used for many years in the most competitive foreign yards and is described in detail in [8] and [9]. It is summarized in the following paragraphs. The methodology for selecting a particular production plan and developing a feasible schedule has not yet been developed from a quantitative point of view. Section 3 presents a model of the associated decision problem, and Appendix A contains a mathematical statement of the model.

2.1 Product Oriented Work Breakdown and Zone Outfitting

The PWBS divides the shipbuilding process into three basic types of work, hull construction, outfitting, and painting, and further classifies each type of work as fabrication or assembly. Interim products are classified by resource requirements and certain product features such as type of system (e.g., lighting system) and zone (any geographical division of the ship). It is noted that PWBS bears a close resemblence to group technology. It is quite flexible and allows activities to be summarized in many different ways.

Zone outfitting is to outfit activities what hull block construction is to steel activities, i.e., it is a logical method for organizing the work to improve planning and productivity. Zone outfitting incorporates three stages for outfitting: on-unit, on-block, and on-board.

Outfitting on-unit refers to the assembly of an interim product consisting of only outfit materials. Examples are water distilling unit, fuel oil purifier unit, pipe passage unit, pump room flat unit, etc. Outfitting on-unit impacts the shop-related resources and the material handling facilities. It may require additional labor and materials for struc-

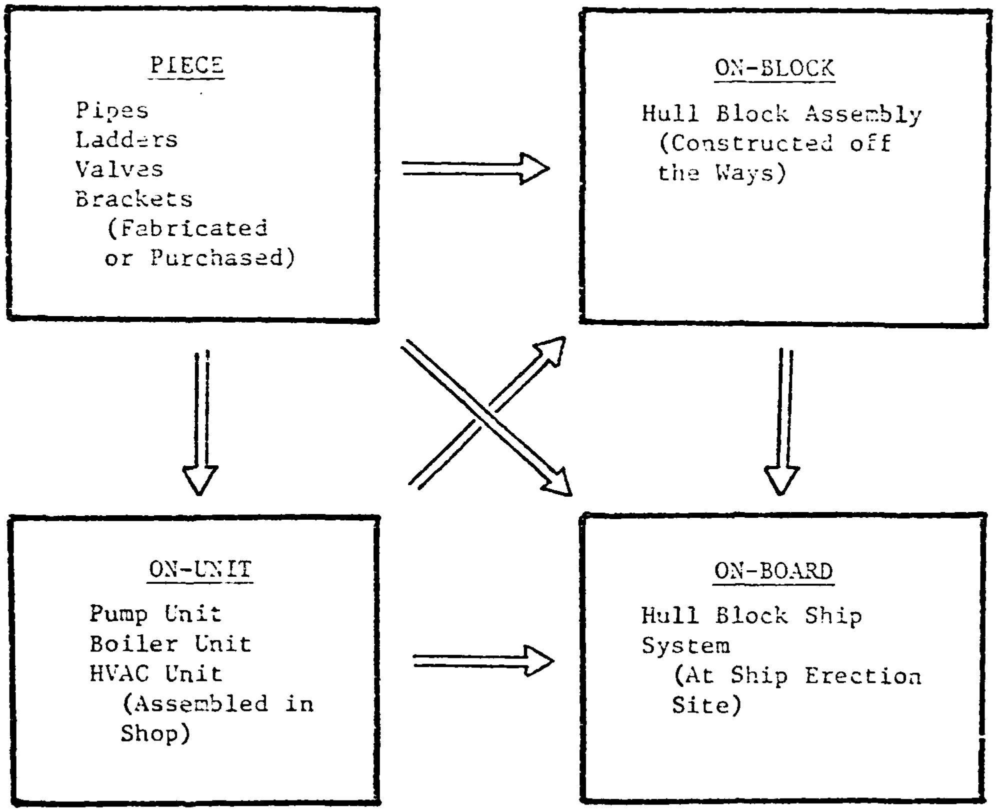


Figure 3. Outfitting Stages

tural support to units to permit their movement to the assembly or ways areas. It also has some impact on hull construction progress since the unit must be landed. However, "on-unit outfitting should be given the highest priority ... because assembly is performed in shops which provide ideal climate, lighting, and access" [8].

Outfitting on-block refers to the installation of outfit components, or units, in a hull block in the assembly area prior to its erection on the ways. Outfitting on-block is more difficult than outfitting on-unit because it requires careful coordination between the steel activities and the outfit activities (recall that there are usually two distinct planning and scheduling functions) and may impact the duraction of a block's occupation of an assembly area.

Outfitting on-board includes any required outfitting activity which has not been performed in either of the two previous stages. Although outfitting on-board describes outfitting as usually practiced, it also allows for non-traditional activities such as the connection of outfit units or outfitted blocks.

Figure 3 illustrates the possible material flows among the zone outfitting stages. Both on-unit and on-block outfitting stages correspond to the previously defined assembly mode of production, although either one could occur in a shop facility. Similarly, the on-board outfitting stage can correspond to either the erection mode or the outfitting mode as previously defined.

Clearly, a full implementation of the zone outfitting approach requires an outfit planner to think in terms of interim products, rather than systems. Furthermore, zone outfitting requires close coordination between steel and outfit schedules. Thus, zone outfitting and PWBS are mutually reinforcing approaches to ship production.

2.2 The Outfit Planning Problem

Because zone outfitting defines various stages for outfitting, it admits *alternatives* for the execution of outfit activities. Thus, the full exploitation of the zone outfitting concept requires that production management be able to resolve all the alternative choices available. The problem of choosing among the many available outfitting plans, which is referred to here as the outfit planning problem, is not currently faced by production management in U.S. shipyards, simply because options are not considered. The following paragraphs begine to suggest the types of options that do exist.

Although there are options in zone outfitting, not every activity can be performed in all three of the outfitting stages. There are some outfit components which are only installed in the on-board stage e.g., furnishings and other similar materials which are subject to damage or pilferage are always installed in the on-board mode. These will be designated *on-board components*. Of the remaining components, some are associated with distributed systems, e.g., wireways or ventilation ducting, rather than distinct units, e.g., pumps, motors, valves, etc. These will be referred to as *non-unit components*, since outfitting on-unit is not appropriate. Finally, there are the outfit components which could be identified by or associated with a specific unit. These will be referred to as *free components*, since any stage may be selected (although on-unit outfitting is preferred).

Note that these designations are fixed to some extent by design practices. For example, a given system consisting of, say, a pump and piping, may be conceived and designed in several ways. If it is treated simply as a collection of separate components which must be installed in the ship,

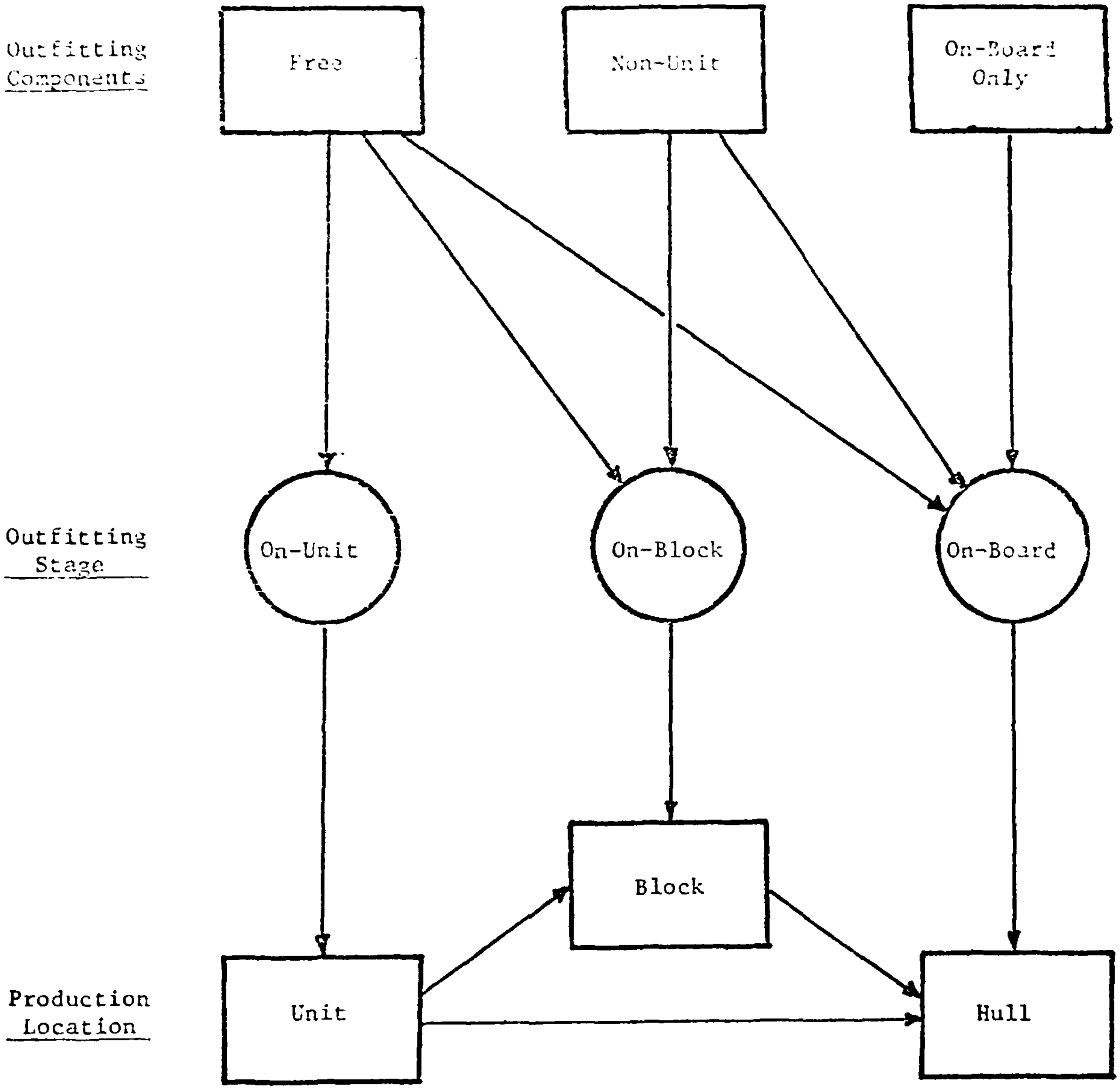


Figure 4. Relationships Between Outfit Components, Outfitting Stages and Production Location

then the components will have the "non-unit" designation. Alternatively, if the components are viewed as integral parts of a single unit or set of units, then they will have the "free" designation. Chirillo and Jonson [8] give examples of outfit components that may be associated with units, although this practice is not typical in U.S. shipyards.

Although a free outfit component can be associated with a specific unit, it need not be installed in the on-unit stage. The component may instead be installed on-block or even on-board. Non-unit components may be installed either on-block or on-board, but not, of course, on-unit. As indicated in the outfitting stage definitions, units may be installed either on-block or on-board. These relationships are summarized in Figure 4 where a three-way distinction is made between the component type, its production stage, and the production location.

Outfit planning requires, for each outfit component, a selection of outfit stage. The selection decisions are constrained by a number of factors. In particular, it is common practice to take the hull block erection schedule as fixed when planning the outfit activities. For example, each hull block has a fixed deadline for its completion, and at that point in time it is lifted onto the ways for erection. Thus, all on-block outfitting planned for that hull block must be completed before its erection date. Similarly, if a unit is to be installed in the block, all the associated on-unit outfitting must be completed in time to allow the unit to be moved onto the block and installed before the block erection date. Furthermore, if the block "closes in" any previously erected blocks, any large components (main engine, diesel generators, etc.) must be landed in these blocks prior to closing in.

The hull block erection schedule is a constraint in outfit planning because of convention. It is also possible to treat the hull block erection schedule as part of the decision process, i.e., if it were justifiable, a hull block might be delayed to allow more on-block outfitting to be performed. This practice does not appear to be in use currently in the U.S., and is not considered in the developments to follow. It is, however, common in Japanese shipyards, and may be adopted by U.S. yards in the future.

Another constraint which may affect outfit planning decisions in many yards is the available lifting capacity. Outfit units and outfitted hull blocks must not exceed the safe lifting capacity of the available equipment. Size is a similar consideration, i.e., units must be sized in light of the available access.

The effect of outfit planning decisions on limited yard resources must also be considered. Among the resources to be considered are labor and material availability and production or storage space. When determining outfit stages, care is required to insure that the resulting production schedule does not call for more labor than is available in each affected craft and grade. Likewise, since production typically requires space and fabricated components or units may need to be stored temporarily, the available yard facilities must not be overcommitted.

These resource allocation considerations are perhaps the most difficult aspect of outfit planning, especially in situations where multiple ships are in production simultaneously. The reason is that in order to quarantee feasibility of the mode selections, a feasible schedule must be determined. The selection decisions and subsequent scheduling decisions interact in a complex fashion and cannot be made independently.

There has been no discussion as yet of the specific criteria by which the outfit plan is to be evaluated. Several criteria may be considered, all motivated by economic considerations. Considerable cost savings are indicated [6, 8] for outfitting on-unit and on-block, relative to outfitting on-board. These cost savings result from lower skill requirements, better material access, less congestion, better quality control, etc. One criterion, which should be minimized, is total cost of outfitting.

Another result of increased on-unit and on-block outfitting would be reduced delivery time. Reducing delivery time is favorable to both owner and builder, since the owner has use of his ship sooner and the builder receives final payment sooner. In addition, they both benefit from the reduced ". . . interest costs for the substantial accumulating investment represented by construction progress and for achieving maximum utilization of expensive facilities such as a building dock" [8]. Thus a second criterion, to be minimized, would be completion time. In particular circumstances, yet other criteria might apply.

The <u>outfit planning problem</u> can now be stated more precisely as follows:

Given:
(1) a catalog of the outfit phase activities for which there are outfitting options;
(2) for each such activity, a list of the outfitting options, including time, resource and precedence requirements;
(3) the ship delivery schedule and any fixed milestone deadlines;
(4) labor availability by craft and grade;
(5) facility capacities and availabilities (lifting, dovered space, yard space, etc.); and
(6) other constraining factors (material availability, rate of cost accumulation, etc.).

Determine: The outfitting option to be used for each outfit phase activity considered, along with the necessary schedule.

The outfit planning problem is one of selecting from a number of interrelated options, a set of options that will satisfy the given resource constraints while optimizing some criterion, such as outfit costs or delivery date.

3. MODEL FORMULATION

Modelling the problem involves the use of activity network models such as CPM or PERT [29, 30, 31, 32, 33]. For practical as well as academic reasons (see, e.g. [14, 24]), only deterministic, i.e., CPM-like, models will be considered.

The use of deterministic activity networks, or DANs [16], to model ship production requires some assumptions about the ship building process.

A1: Ship specifications, such as production drawings, can be converted into well defined, distinct work packages, or activities.

A2: Assuming unlimited production resources, the only relationship between the activities is one of sequence or precedence. An activity, "A," precedes another activity, "B," if "A" must be completed before "B" can be initiated.

These two assumptions permit graphical representation of the relationship between production activities. The one used in this research is the activity on node, or AON, representation [16].

Note that assumption A2 does not limit the relationships between activities to precedence only. Other types of relationships are possible, for example, two activities may require the use of the same limited resource.

A3: Associated with each activity is information about its duration (including resource-time options), about its requirements for various resources, and about its due date (or completion deadline) if appropriate.

In order to use the DAN model in planning, it must include certain information about the activities or work packages beyond precedence relationships. At a minimum, each activity has a given duration and resource consumption. In addition, it is often the case that the activity duration depends on the rate at which resources are applied, i.e., there are resource-duration options. Start and due dates are often imposed because of special considerations beyond just the work content of the project, e.g., a hull erection schedule.

> A4: The various resources required to perform the activities are explicitly defined and the availability of the resources over the planning horizon is specified.

The resources required by the activities can be of two types. Some resources are consumed as they are applied to production, e.g., steel which is applied to a particular hull block. Any subcontracted material falls into this category. This type of resource must be available when the associated activity is scheduled.

The other resource type is available at a certain rate rather than a total amount. For example, a given labor pool in a particular craft translates into a fixed number of man hours per day of that resource. Of course, over the long run, the number of man hours can be changed by changing the size of the labor pool. Thus, this type of resource is not "used up" in the same way that materials are.

Resources of this type present more difficult planning problems. One reason is that the cost of the resource depends on the rate at which it is used, i.e., if the resource is not fully utilized in some period, there is a wasted resource cost. Thus, one goal is to schedule the production activities so that resources of this type are always fully utilized.

The classical DAN models, such as CPM, are inadequate for the outfitting planning problem because they are based on the assumption of a single, unambiguous definition of the activities. In contrast, the essence of the outfit planning problem is to select a particular activity definition (i.e., select production modes) from among all the available alternatives. It will be necessary to extend the DAN models to incorporate this additional complexity and to develop the corresponding extensions to the analytic methodologies.

3.1 An Activity Network Model of the Outfit Planning Problem

The goal of the following discussion is the development of a conceptual model for the outfit planning problem which is consistent with an activity network based approach to planning and scheduling. It must be recognized at the outset that the process being modelled exists only hypothetically and that the model does not represent any existing process. It is apparently the case that, at the present time, very few U.S. shipyards employ activity network based planning or scheduling procedures in production, thus, the proposed model constitutes a significant departure from currently standard practice. On the other hand, it is also apparently true that interest in this type of methodology is growing in many U.S. shipyards, so that the proposed model is in line with longer term trends in the industry and is based upon some elements currently recognized in the industry.

3.1.1 Defining the Activities

Current practice in U.S. production planning ([1], appendix 4) calls for work packages of 200-2000 man-hours, involving a single craft or trade. For comparison, the Japanese practice [8] is to define work packages of 40-120 man-hours. The following developments are based on the premise that activity descriptions can be made at the level of the smallest fabricated component and then aggregated as necessary. Furthermore, an activity, as discussed in the previous section, may consume different resources, i.e., it may involve two or more crafts. The organizational and operational ramifications of this departure from standard practice will be explored later.

In developing the model, it will be useful to maintain the distinction between outfit components, which are associated with the outfit materials, and the outfit activities, which are associated with production, i.e., fabrication, assembly and installation. The outfit components were categorized as on-board, non-unit, or free, and outfit activities were classified as on-unit, on-block or on-board. The question which follows from this classification scheme is, "How are the activities corresponding to a given outfit component defined?"

A fundamental assumption about outfit planning is:

A5: On-unit outfitting is preferred to on-block outfitting, which is preferred to on-board outfitting.

This assumption implies that if there were no resource conflicts, or time constraints, outfitting would always be done as early as possible in the production process. It is the resource conflicts and milestone event deadlines which lead to deviations from this "ideal" outfitting plan.

Free Outfit Components

The free outfit components present the greatest latitude in planning production since they may lead to on-unit, or on-block, or on-board production activities, or to a combination. As a consequence, these are the activities that present the most difficulties in formulating the DAN model of outfit planning.

The "ideal" outfitting plan would call for maximum use of the on-unit stage, with the resulting units being installed whenever possible. Thus, the following assumption is made:

> A6: The outfit planning process creates for the free outfit components, a catalog of maximally outfitted units. For each unit, all the required materials, fabricated pieces and assembly work elements are specified. The set of outfit work elements for a given unit will be referred to as the <u>maximum</u> <u>outfit</u> set for the unit.

A particular unit from this catalog will generate many individual activities in the model (recall that the individual activities may be aggregated at a later step in the planning process). For example, each individual component of the unit must be either fabricated or purchased, resulting in the definition of either a fabrication activity or a purchasing activity. Each subassembly operation likewise results in the definition of a distinct activity.

An implicit requirement is that the units in this catalog are non-overlapping, i.e., no free outfit component is a component of more than one unit. Thus, the definitions of the units themselves are considered as fixed at an earlier stage in the planning process. The problem of selecting from among alternative unit definitions is included in the proposed model in certain fairly restrictive situations as seen later.

It may be the case that selection of the on-unit outfitting rather than on-block or on-board "induces" additional work elements. For example, additional bracing may be required to prevent damaging the unit during handling and moving. Any such induced work must be reflected in additional activities in the DAN model.

Since the ideal outfitting plan may not be feasible given the available resources and milestone event deadlines, it is necessary to specify the alternatives to be allowed within the outfit planning model.

> A7: For each unit, there is a set of outfit components which represents the least amount of on-unit outfitting that can be done and still be economically justifiable. The associated set of outfit work elements will be called the minimum outfitting set for the unit.

This assumption implies that if a particular unit is selected from the catalog for on-unit outfitting, it need not be completely outfitted. However, it will include at least those outfit work elements contained in its minimum outfitting set. Associated with the maximum and minimum outfit sets are related sets of outfit components, designated as the maximum and minimum outfit kits.

A given unit may be assembled in the on-unit mode. If so, it must include all components in its minimum outfit kit and it may include any additional components in its maximum outfit kit. Any work elements from the maximum outfit set which are not selected for on-unit outfitting must be performed at a subsequent stage, i.e., either on-block or on-board. The outfitted unit itself also may be installed on-block or on-board. If installed on-block, its assembly and installation must be completed before the block erection deadline.

These possibilities can be incorporated in a CPM-like precedence diagram as illustrated in Figure 5. In this example, nodes 1-4 represent the purchase, fabrication, or subcontracting activities for outfit components in the maximum outfitting kit for some unit. The components corresponding to nodes 2, 3 and 4 are in the minimum outfitting kit for the unit, i.e., at least these components must be included if the unit is selected for fabrication.

A component, such as the one corresponding to node 1 in the figure, which is in the maximum outfitting kit has the following characteristic. It is a component which could be included in the unit fabrication and, in

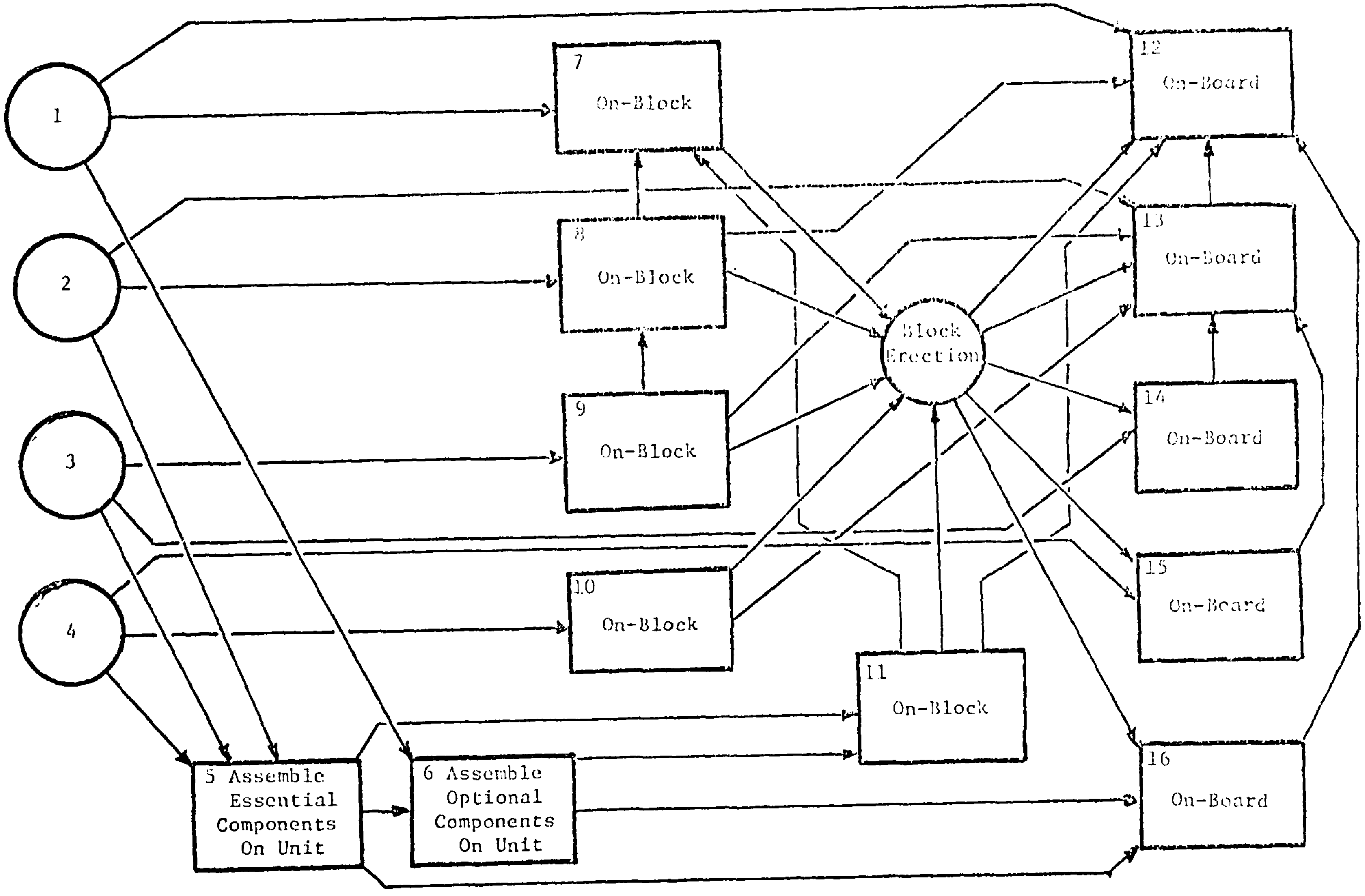


Figure 5. Activity Model for Free Outfit Components

fact, it would be desirable to include it. However, if there are frustrating circumstances, for example, insufficient fabrication lead time or insufficient resources (labor, equipment, or material), then such a component may be left off the unit. It is, in a sense, an auxiliary component of the unit. On the other hand, components in the minimum outfitting kit are considered essential to the unit, so much so that they cannot be omitted from the unit.

The activities represented in the diagram by square nodes are the ones subject to the outfit planning decisions, which designate the specific stage of outfitting for each component.

To insure that components produced by the first four activities in Figure 5 are actually installed, the outfit planning decisions must obey the following guidelines:

(1) Exactly one activity is selected from each of the sets:
{6,7,12} to insure that component 1 is included;
{5,3,13} to insure that component 2 is included;
{5,9,14} to insure that component 3 is included;
{5,10,15} to insure that component 4 is included;
If activity 5 is selected, activities 8, 9, 10, 13, 14, and 15 cannot be selected.

(2) Activity 6 can be selected only if activity 5 is selected;

(3) If activity 5 is selected, then either 11 or 16 must be selected; if 5 is not selected, neither 11 and 16 can be.

If these three guidelines are followed, then a feasible solution will be constructed for the outfit planning problem. Note that if an activity is not selected, it simply becomes a discarded option, i.e., it does not affect subsequent scheduling or resource allocation decisions.

The example illustrates additional details that can be incorporated in this type of model. For example, if in addition to the minimum outfitting kit, component 1 is also to be included in the on-unit outfitting (i.e., activity 6 is selected) the associated work element, activity 6, must be completed by the time the unit is installed, either on-block (activity 11) or on-board (activity 16). This is indicated by the precedence relationships (5, 6), (6, 11) and (6, 16).

In this example, there is a required sequence for installing the outfit components: component 2 cannot be installed until after components 3 and 4 have been installed, and component 1 cannot be installed until after component 2 has been installed. These restrictions are satisfied by requiring that activity 13 has as its predecessors, either 9 or 14, and either 10 or 15. Similarly, activity 12 has as predecessors either 8 or 13. Note also that if activity 5 is selected (i.e., the unit is assembled) then on-block or on-board outfitting for component 1 must *follow* installation of the unit.

Finally, note that the block erection schedule can be introduced into the model simply by specifying a due date for the unnumbered node corresponding to block erection. One additional consideration was left out to simplify the figure and the discussion. It might be desirable to treat on-board outfitting as two distinct stages, one corresponding to pre-float off outfitting and one corresponding to wet-dock outfitting. This consideration could be affected within the model simply by defining four additional nodes, one for each of the four outfit components, and adding the necessary precedence relationships. This is illustrated for the previous example in Figure 6.

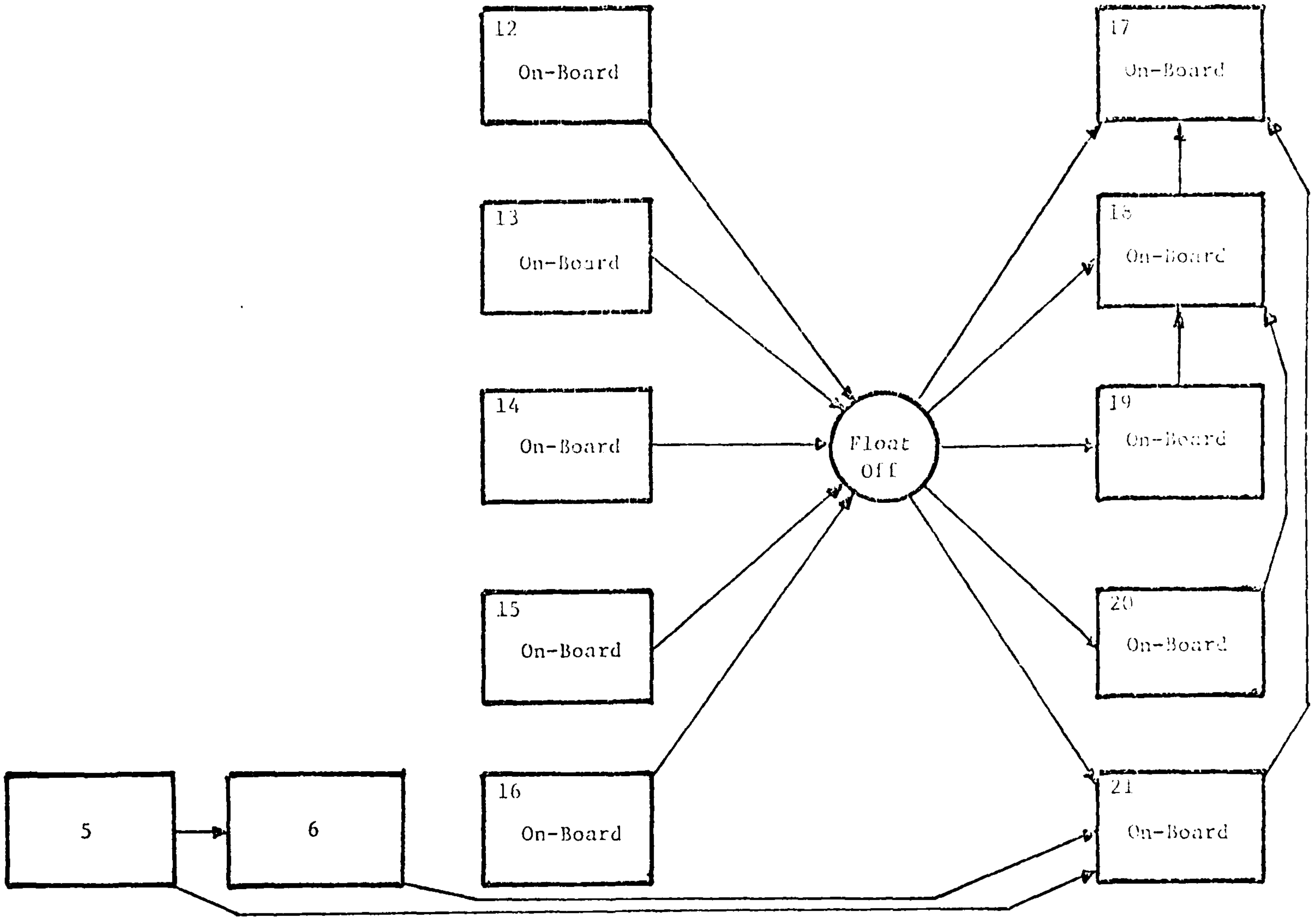


Figure 6. Adding Two Sub-Stages to the Model

Non-Unit Outfit Components

The non-unit outfit components involve fewer production options than the free outfit components and it is therefore considerably easier to define the alternative activities generated by them. In fact, non-unit components generate a subset of the activities generated by free components. For instance referring to the example of Figure 5, suppose the on-unit outfitting activities, which are activities 5, 6, 11, and 16, are omitted. The resulting activity network would describe the options available for non-unit components 1-4.

In addition to sequencing requirements among the non-unit components, there may also be sequencing requirements between the non-unit components and certain free components or their associated units. The various types of relationships are summarized in Figure 7. As indicated in the figure, the model must account for the possibility of sequencing requirements between the non-unit components and certain free components or their associated units, as well as between the non-unit component and certain on-board components.

As with the free outfit components, it is conceptually easy to extend the model to allow two distinct on-board outfit stages. The illustration will not be repeated.

On-Board Outfit Components

The on-board outfit components require no outfitting mode decision, unless the possibility of two on-board stages (pre-float off and wet-dock) are allowed. In this case, each component generates two alternative outfitting activities with precedence relationships as shown in Figure 8. The requirement, then, is to select exactly one of the two activities.

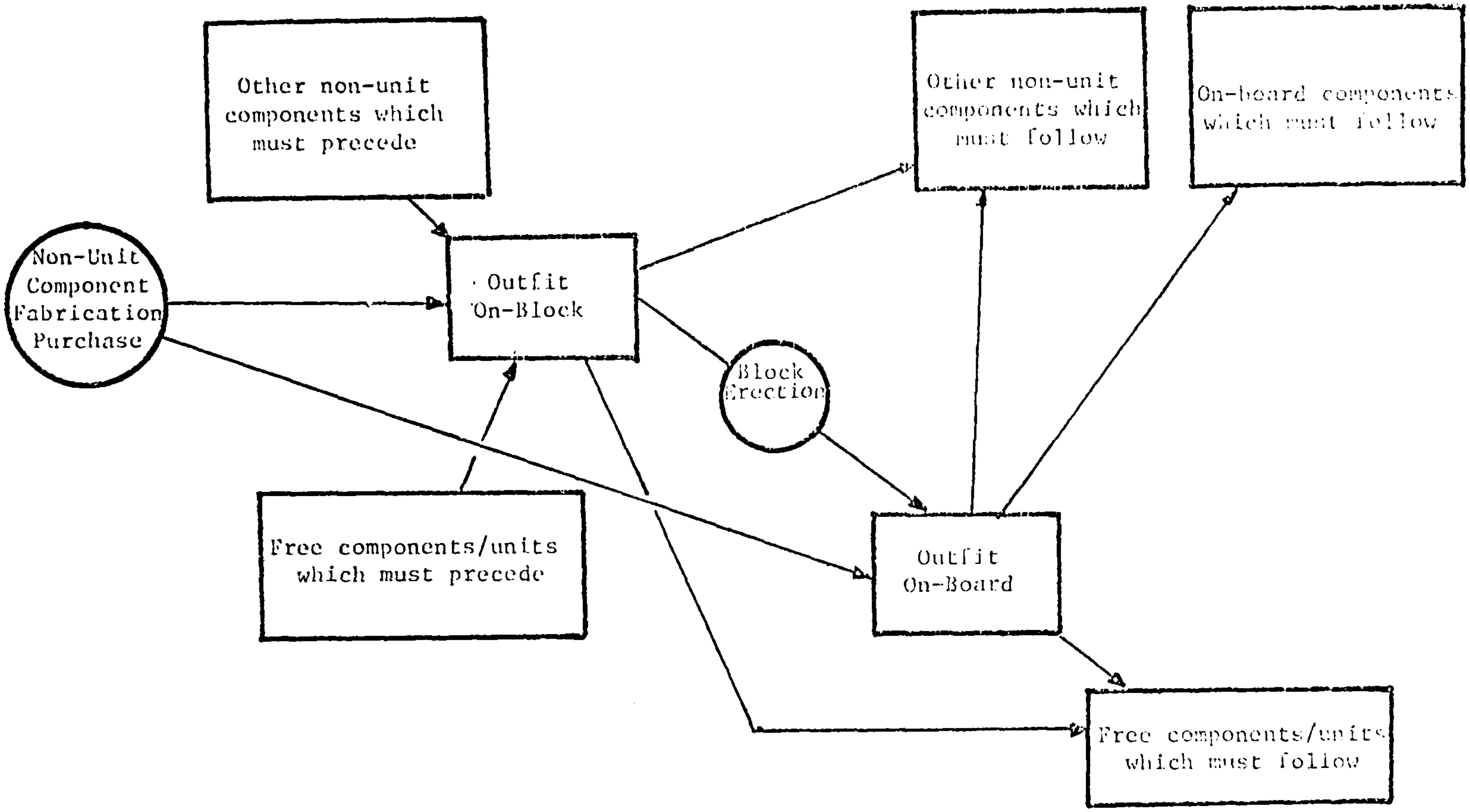


Figure 7. Activity Model for Non-Unit Components

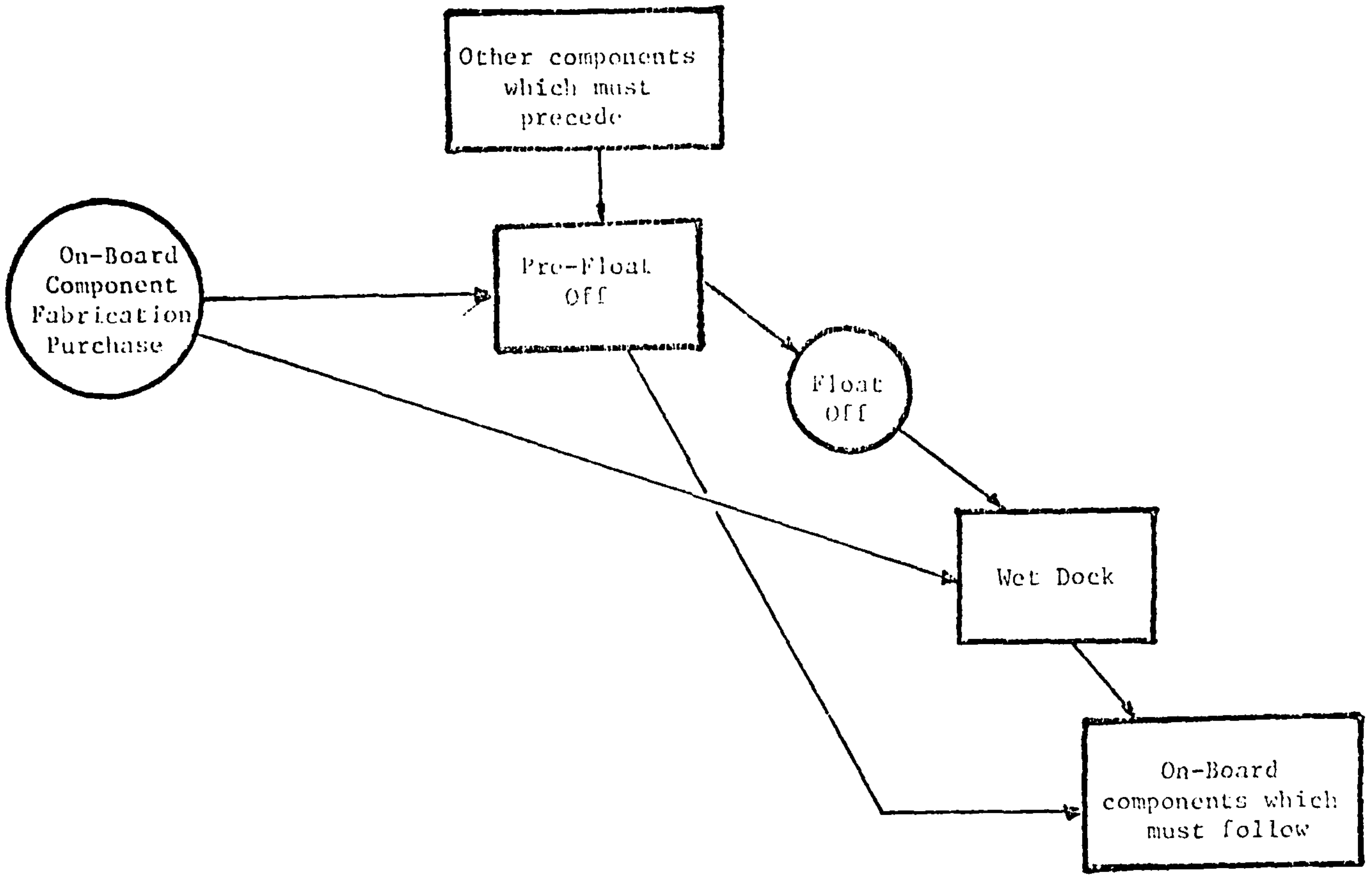


Figure 8. Activity Model for On-Board Components

3.1.2 Defining the Decisions and Constraints

The fundamental decision required in the outfit planning problem is the resolution of the options associated with each outfit component. This selection decision considers the activity network and requires a choice of exactly one of the alternative outfit activities for each outfit component (and perhaps the resulting unit). The selection decision must satisfy the sequencing requirements which are represented in the activity network as arrows. The sequencing requirements are constraints on the selection decision.

If there were no other constraints, the selection decision would be trivial because of assumption A5, i.e., each component would be outfitted as early as possible in the production process. There are, however three major types of constraints which may be violated by such a selection:

(1) [Time] The sequencing requirements may lead to a longer production time at some stage than is available from the given block erection and float-off milestones.

(2) [Labor] Even if there is sufficient time, the activities selected to be performed between two milestones may require more labor hours than are available in the crafts.

(3) [Weight and Size] Even if there is sufficient time and labor, the number of components selected for a unit or the number of units and components selected for a block may lead to a unit or block which is too large for the available facilities or access.

The constraints on time and weight may be easily checked once the selection decision is known. Such is not always the case, however, for the labor availability constraints.

In order to know whether or not a labor availability constraint is satisfied, a schedule for the activities must be specified. Thus, in situations where labor availability is a limiting factor, solving the outfit planning problem requires making a scheduling decision in addition to the selection decision.

The scheduling decision by itself is an extremely complex one. In fact, given the selection decision, the problem to be solved in making the scheduling decision is a "resource constrained CPM problem," [5, 12, 49, 50]. At the present time there is no optimization algorithm capable of solving large instances of this type of problem (see Bennington and McGinnis [5]) and based on recent results in combinatorics ([28], [44]) there is little hope that such an algorithm is possible. Thus, if solving the outfit planning problem requires a specific scheduling decision, any practical solution methodology will be heuristic in nature.

3.1.2.3 Defining the Criteria

The final step in formulating a model of the outfit planning problem is to define the criteria by which solutions are to be evaluated. The problem of evaluation is complicated by the fact that there are two distinct kinds of decisions being made: outfitting stage selection and activity scheduling. Furthermore, a number of different viewpoints could be considered, each leading, possibly, to a different criterion.

The viewpoint adopted here is that the outfit planning problem is to be solved in the context of a number of prior, exogenous decisions which fix many of the outfit planning problem parameters. For example, the milestone event times (such as lay keel, float off, delivery, etc.) are assumed fixed, along with the detailed block fabrication and erection schedule.

(Note, however, that this analytic framework could be used in deciding on the appropriate milestone schedule.) Resource availabilities are considered as exogenous factors.

Within the environment resulting from these exogenous factors, the goal in outfit planning is narrowed to that of minimizing the cost of outfitting. Conceptually, then, all that is required is to estimate the outfitting cost associated with each of the outfitting alternatives. The best outfitting plan is the one with the smallest total cost. The goal of the scheduling component of outfit planning is to maximize labor utilization. This is accomplished when there are no periods in which the scheduled work content is less than the available labor.

While these two criteria are conceptually simple, their application may be difficult. In the first place, they require a significant effort in detailed estimation. The labor content, material and overhead costs, and duration must be estimated for each of several alternative outfit methods for a large number of outfit components. Current practice may not require such a detailed estimate for even one alternative. Clearly, procedures and methods will need to be developed for aggregating outfit components in the activity network and for semi-automating the estimation at the necessary level of detail. The information required for this estimation process will have to be accumulated over time as there is more experience with on-unit, on-block, and on-board outfitting.

A preliminary and crude approach to the first criterion is the following. Assume that the savings to be realized by outfitting earlier in the production process is a constant fraction of the total cost to outfit on-board. The fraction could vary with the type of outfitting (e.g., electrical vs. hydraulic systems), or with the total cost of the outfitting activity or some other factor. The criterion then becomes one of maximizing the total savings over outfitting completely on-board.

3.2 Model Evaluation

A mathematical model has been developed to describe the outfit planning problem and appears in Appendix A. This model is in the form of a mixed integer programming problem and, consequently, it presents formidable difficulties in solution. In fact, recent theoretical development [28] have been interpreted as indicating that such problems (referred to as "NP-complete") cannot be solved optimally. Certainly it is true that, currently, practical problems of this ilk are not optimized. There are, however, a number of heuristic solution procedures which have been developed and used successfully to solve similar problems (e.g., see [37]).

Obviously, the model by itself cannot lead to better outfit planning. What is required is a systematic implementation of the model. There are several requirements for a successful implementation of the model, and these can be more easily discussed by referencing the diagram of Figure 9.

One of the requirements for a successful implementation is an appropriate methodology for solving the selection and scheduling problem for given milestone events and resource availabilities. As was indicated earlier, there is little hope for a general optimizing method for solving this problem, so in the most general case, the solution procedure will be heuristic.

The model requires large amounts of information and generates large numbers of detailed decisions. Thus, any practical implementation will require a fairly detailed, production oriented data base to support the solution procedure. Although many shipyards do not have such a data base at the current time, the SPARDIS system used by NASSCO [45] is one example of the type of system that would be required.

A third requirement is that the outfit planning process could in fact provide all the information required in the model. It appears that a major shift from current practice would be the idea of allowing (and therefore planning for) several alternative ways to accomplish the outfitting tasks. In addition, the use of the on-unit, on-block, on-board approach to outfitting is not currently widespread, although it is being strongly supported as a means for improving productivity [8].

Given that the zone outfitting approach has been adopted, defining the alternative outfit activities discussed earlier should be straightforward, albeit somewhat time-consuming. Observe that to a large degree, the outfit elements are associated with particular blocks. Therefore, a activity network resembles a large number of small subnetworks (one for each block) which are loosely connected by milestone events. It will be possible to "decompose" the network definition into smaller, more manageable tasks.

Figure 9 also indicates how the model might be used in practice. The use of the model for planning the outfitting of a ship as self-evident. Probably as important is the use of the model to "replan" when there are major deviations from the original plan, e.g. due to weather, change orders, priority repair work, etc.

A final point of discussion is the benefit to be obtained by the use of the model. The foremost benefit of the model, per se, is tighter planning and control of outfitting, resulting in higher productivity (and thus lower costs). In project-type work, such as ship production, it is important to correctly estimate the labor content of the work and then plan the work so that labor resource utilization is maximized. The proposed model

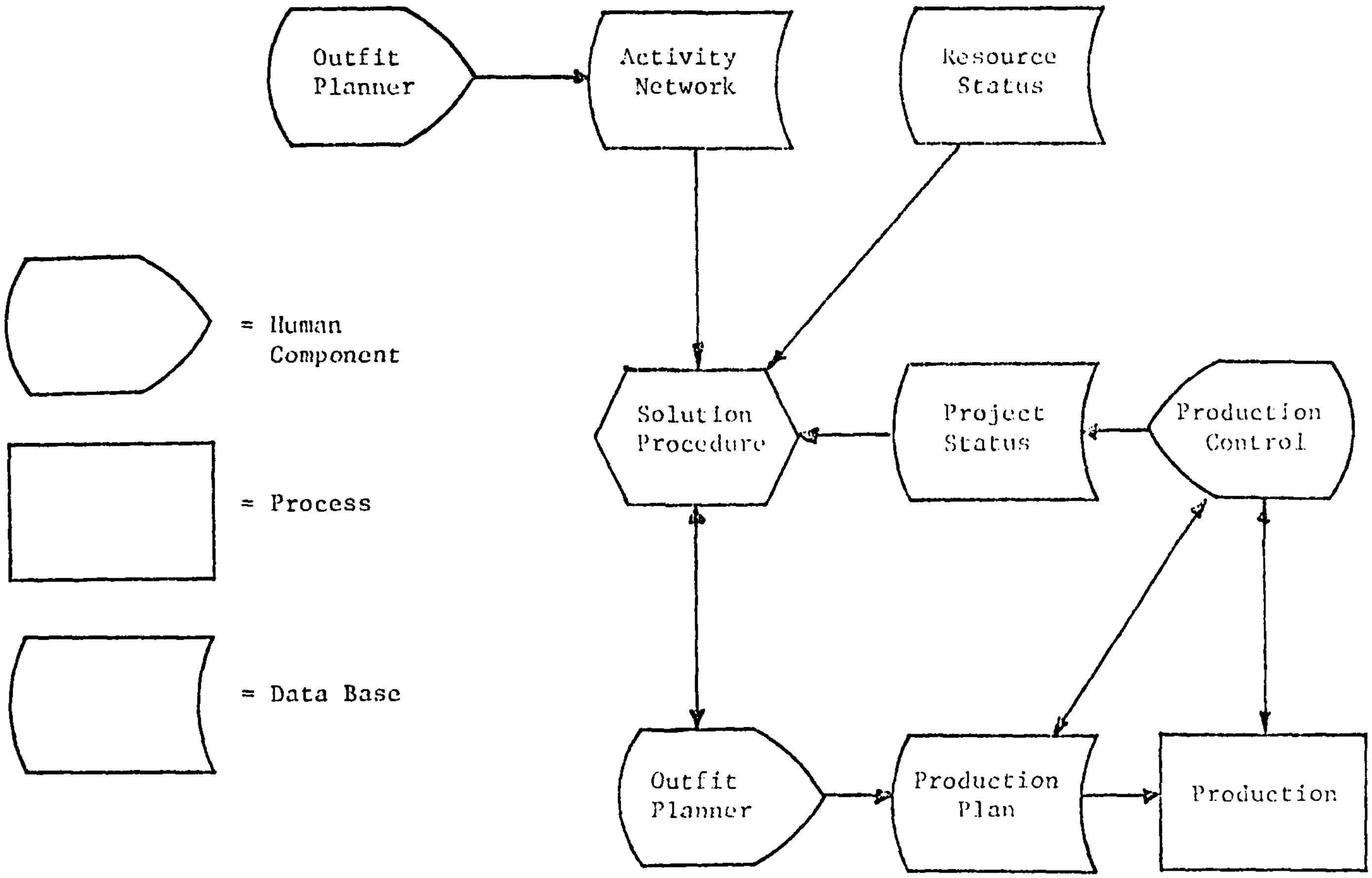


Figure 9. Outfit Planning Process

provides a systematic means for coping with and coordinating the vast number of relationships which simply cannot be handled by an unaided human planner.

A secondary benefit from the proposed model is that it complements and strengthens the implementation of the on-unit, on-block, on-board approach to outfitting. It provides a systematic framework for identifying opportunities for on-unit and on-block outfitting as well as for determining the technical and economic feasibility of outfitting plans.

APPENDIX A: The Mathematical Model

In developing the conceptual model, two types of decisions were identified: selection decisions and scheduling decisions. It will be convenient to formalize the selection decisions first. Associate with each outfit component an index, i, where i = 1, 2, ..., N, N being the total number of outfit components. Similarly, associate with each outfit unit an index j = 1, ..., M, and with each block an index b = 1, ..., B.

The selection decisions will be represented by indicator variables. For a particular component, i, the variables are:

$$x_i^u = \begin{cases} 1 \text{ if component i is outfit on-}\underline{\text{u}}\text{nit} \\ 0 \text{ otherwise} \end{cases}$$

$$x_i^b = \begin{cases} 1 \text{ if component i is outfit on-}\underline{\text{b}}\text{lock} \\ 0 \text{ otherwise} \end{cases}$$

$$x_i^h = \begin{cases} 1 \text{ if component i is outfit on-board} \\ \text{(in the }\underline{\text{h}}\text{ull)} \\ 0 \text{ otherwise} \end{cases}$$

Exactly one of the indicator variables must equal one for any component. However, not all stages can be selected for each element. Therefore, group the indices as follows:

F = set of indices of free outfit components

N = set of indices of non-unit outfit components

B = set of indices of on-board outfit components

These sets are pairwise disjoint. Now the component selection decisions must satisfy:

$$x_i^u + x_i^b + x_i^h = 1 \qquad i \in F \tag{1}$$

$$x_i^b + x_i^h = 1 \qquad i \in N \tag{2}$$

$$x_i^h = 1 \qquad i \in B \tag{3}$$

Note that there is only one on-board option. The model can be readily extended to allow for pre-float off and wet-dock on-board outfitting. In order to simplify the exposition, this extension is not included.

There are similar indicator variables associated with each unit:

$$z_j = \begin{cases} 1 \text{ if unit j is selected for assembly} \\ 0 \text{ otherwise} \end{cases}$$

$$y_j^b = \begin{cases} 1 \text{ if unit j is installed on-block} \\ 0 \text{ otherwise} \end{cases}$$

$$y_j^h = \begin{cases} 1 \text{ if unit j is installed on-board} \\ 0 \text{ otherwise} \end{cases}$$

Since a unit cannot be installed unless it is first assembled, the unit selection variables must satisfy the following constraint:

$$y_j^b + y_j^h - z_j = 0 \qquad \forall\, j \tag{4}$$

The unit selection decisions and element selection decisions must be tied together. Define the following index sets:

L(j) = set of indices of components in the minimum outfitting kit for unit j

M(j) = set of indices of components in the maximum outfitting kit for unit j

The element and unit selection variables must satisfy:

$$\sum_{i \in L(j)} x_i^u - \|L(j)\| z_j = 0 \qquad \forall\ j \tag{5}$$

$$\sum_{i \in M(j)} x_i^u - \|M(j)\| z_j \leq 0 \qquad \forall\ j \tag{6}$$

where $\|S\|$ is the number of elements of the set S. Constraint (5) requires that if unit j is selected ($z_j = 1$), then all the components in the minimum outfitting kit for that unit also must be selected. Constraint (6) permits additional components to be included in the unit only if the unit is fabricated.

The constraints (1)-(6) are <u>logical constraints</u> and merely guarantee consistency between the indicator variables and the decisions they represent. In addition, there are <u>structural constraints</u> which must be satisfied. One of these is the precedence relationships defined by sequencing requirements. Define

P(j) = index set of components (units) which must precede component (unit) j in production.

Then the precedence constraints on the selection decisions are:

$$x_i^u + 2x_i^b + 3x_i^h - (x_j^u + 2x_j^b + 3x_j^h) \leq 0 \qquad i \in P(j) \tag{7}$$

$$y_j^b + 2y_j^h - (y_k^b + 2y_k^h) \leq 0 \qquad j \in P(k) \tag{8}$$

Constraints (7) and (8) require that for any component or unit, its predecessors must be outfitted or installed at the same or an earlier production stage.

A second category of structural constraints limits the total weight added to a unit or block. Note that these limits may be facility dependent, i.e., units fabricated in different shops may have different weight limits.

$$\sum_{i \in M(j)} w_i x_i^u \leq W_j \qquad \forall\ j \qquad (9)$$

$$\sum_{j \in U(b)} \left(\sum_{i \in M(j)} w_i x_i^u \right) y_j^b + \sum_{i \in F(b) \cup N(b)} w_i x_i^b \leq W_b \qquad \forall\ b \quad (10)$$

where:

w_i = weight added by outfit element i

W_j = maximum weight allowed for unit j

$U(b)$ = units which go into block b

$N(b)$ = subset of components of N which go into block b

$F(b)$ = subset of components of F which go into block b

W_b = maximum outfitting weight added to block b

The first term in constraint (10) is the total weight of units which are selected for installation on-block. The second term is the total weight of components (not part of a unit) which are outfitted on-block.

In order to deal with the time and labor availability constraints, the scheduling decisions must be formalized. Define the following scheduling variables:

t_i = scheduled start time for component i outfitting

θ_j = scheduled time for completing unit j fabrication

τ_j = scheduled start time for unit j installation

The scheduling variables must satisfy all the precedence constraints as well as the scheduling limitations imposed by the steel schedule.

First, consider the constraints involving on-unit outfitting.

$$t_i x_i^u + d_i^u x_i^u - t_j x_j^u \leq 0 \qquad i \in P(j) \qquad (11)$$

where d_i^u = time to outfit component i on unit.

Constraint (11) requires that all predecessors of component j must be completed before component j can be outfitted on unit.

$$t_i x_i^u + d_i^u x_i^u - \theta_j z_j \leq 0 \qquad \forall\ i \in M(j) \qquad (12)$$

Constraint (12) requires all on-unit outfitting to be completed before the unit itself is completed.

$$\theta_j + d_j - \tau_j \leq 0 \qquad \forall\ j \qquad (13)$$

where d_j = material handling delay for unit j.
Constraint (13) is included to allow for possible significant material handling delay or resource requirement.

The installation of units and outfit components on-block must not only satisfy precedence but "schedule window" constraints as well.

$$\tau_j y_i^b + d_j^b y_j^b - \tau_k y_k^b \leq 0 \qquad j \in P(k) \qquad (14)$$

where d_j^b is the time required to install unit j on-block.
Constraint (14) forces the on-block installation of unit k to be after the on-block installation of its predecessors.

$$\tau_j - T_b^s \geq 0 \qquad \forall\ j \in U(b) \qquad (15)$$

where T_b^s = earliest possible time for on-block outfitting on block b.
Constraint (15) forces the installation of the unit j to be after the time when installation is feasible.

$$\tau_j y_j^b + d_j^b y_j^b - T_b^f \leq 0 \qquad \forall\ j \in U(b) \qquad (16)$$

where T_b^f = latest possible time to complete outfitting on block b.

Constraint (16) sets the deadline for on-block installation of units.

There are similar precedence and schedule window constraints for the on-block outfitting of free and non-unit components:

$$t_i x_i^b + d_i^b x_i^b - t_j x_j^b \leq 0 \qquad j \in P(i) \qquad (17)$$

$$t_i x_i^b - T_b^s x_i^b \geq 0 \qquad i \in F(b) \cup N(b), \qquad \forall\, b \qquad (18)$$

$$t_i x_i^b + d_i^b x_i^b - T_b^f \leq 0 \qquad i \in F(b) \cup N(b), \qquad \forall\, b \qquad (19)$$

These same precedence and schedule window constraints are repeated for both units and elements for on-board outfitting. For the units, the constraints are:

$$\tau_j y_j^h + d_j^h y_j^h - \tau_k y_k^h \leq 0 \qquad j \in P(k) \qquad (20)$$

$$\tau_j - T_h^s y_j^h \geq 0 \qquad \forall\, j \qquad (21)$$

where T_h^s = earliest possible time for installing unit on-board.

$$\tau_j y_j^h + d_j^h y_j^h - T_h^f \leq 0 \qquad \forall\, j \qquad (22)$$

where T_h^f = latest possible time for installing unit on-board.

For the outfit components, the corresponding constraints are:

$$t_i x_i^h + d_i^h x_i^h - t_j x_j^h \leq 0 \qquad j \in P(i) \qquad (23)$$

$$t_i x_i^h - T_h^s x_i^h \geq 0 \qquad \forall\, i \qquad (24)$$

$$t_i x_i^h + d_i^h x_i^h - T_h^f \leq 0 \qquad \forall\, i \qquad (25)$$

In addition to precedence and schedule window constraints, the scheduling decisions must be feasible with regard to the resource availabilities. Resource availability constraints are quite difficult to formulate in explicit terms, so the following approach is typically used (see, e.g., models in [5] and [11]). Define the following:

$A_e(t)$ = set of outfit components being outfitted at time t

$A_u(t)$ = set of outfit units being installed at time t

r_{icu} = level of resource category c required by component i when outfitted on-unit

r_{icb} = level of resource category c required by component i when outfitted on-block

r_{ich} = level of resource category c required by component i when outfitted on-board

r_{jcf} = level of resource category c required to fabricate unit j

r_{jcb} = level of resource category c required to install unit j on-block

r_{jch} = level of resource category c required to install unit j on-board

R_{ct} = level of resource category c available at time t.

Now the resource availability constraints are:

$$\sum_{i \varepsilon A_e(t)} (r_{icu}x_i^u + r_{icb}x_i^b + r_{ich}x_i^h) +$$

$$\sum_{j \varepsilon A_u(t)} (r_{jcf}z_j + r_{jch}y_j^b + r_{jch}y_j^h) \leq R_{ct} \qquad (26)$$

The difficulty with using such a constraint is that the sets $A_e(t)$ and $A_u(t)$ depend on the scheduling decisions. In fact this is, to a certain degree, the nub of the resource constrained project scheduling problem.

The constraints (1)-(26) can be shown to be redundant. For example, if the scheduling related precedence constraints, (11)-(25), are satisfied, then the selection related precedence constraints, (7) and (8), must necessarily be satisfied. The reason for including the redundant constraints, (7) and (8), is to allow for solution procedures which try to decouple the selection and scheduling decisions.

Since the criterion specified for the outfit planning problem is to minimize outfitting costs, define:

C_{iu} = cost of outfitting element i on-unit

C_{ib} = cost of outfitting element i on-block

C_{ih} = cost of outfitting element i on-block

C_{jb} = cost to install unit j on-block

C_{jh} = cost to install unit j on-board

The objective function for the mathematical model is:

$$\text{Minimize} \sum_i [C_{iu}x_i^u + C_{ib}x_i^b + C_{ih}x_i^h]$$

$$+ \sum_j [C_{jb}y_j^b + C_{jh}y_j^h]$$

REFERENCE

1. *A Manual on Planning and Production Control for Shipyard Use*, Bath Iron Works, Bath, Maine.

2. Andrews, V. Benjamin, et al., "Conceptual Design of a Mechanized Shipyard for Fast Deployment Logistics (X) Production," National Technical Information Service, U.S. Department of Commerce, AD-752-595, December, 1965, pp. 1-88.

3. Balas, Egon, and Eitan Zemel, "Solving Large Zero-One Knapsack Problems," Management Sciences Research Report No. 408(R), Graduate School of Industrial Administration, Carnegie-Mellon University, Pittsburgh, PA, 1977.

4. Battersby, Albert, *Network Analysis for Planning and Scheduling*, St. Martin's Press, New York, 1970.

5. Bennington, G. E., and L. F. McGinnis, "A Critique of Project Planning with Constrained Resources," *Proceedings of the Symposium on Scheduling Theory and Its Applications*, S. E. Elmaghraby, ed., Springer-Verlag, 1973.

6. Chirillo, L. D., presentation to Chesapeake Section, SNAME, May, 1979.

7. Chirillo, L. D., private correspondence, Todd Pacific Shipyards Corporation, Seattle Division, January, 1979.

8. Chirillo, L. D., and C. S. Jonson, *Outfit Planning Manual*, National Shipbuilding Research Program, Project SP-IV-D, 1979.

9. Chirillo, L. D., and C. S. Jonson, *Product Oriented Work Breakdown Structure*, National Shipbuilding Research Program, in press.

10. Cooper, D. F., "Heuristics for Scheduling Resource-Constrained Projects: An Experimental Investigation," *Management Science*, Vol. 22, No. 11, 1976.

11. Davis, E. W., "Resource Allocation in Project Network Models - A Survey," *Journal of Industrial Engineering*, April, 1966.

12. Davis, E. W., "Project Scheduling under Resource Constraints - Historical Review and Categorization of Procedures," *AIIE Transactions*, Vol. 5, No. 4, 1973.

13. Dewitte, L., "Manpower Levelling of PERT Networks," *Data Processing for Science/Engineering*, Vol. 2, No. 2, 1964.

14. Elmaghraby, S. E., "On the Expected Duration of PERT Type Networks," *Management Science*, Vol. 13, No. 5, 1967.

15. Elmaghraby, S. E., *Some Network Models in Management Science*, Springer-Verlag, 1970.

16. Elmaghraby, S. E., *Activity Networks: Project Planning and Control by Network Models*, Wiley, 1977.

17. Fulkerson, D. R., "A Network Flow Computation for Project Cost Curves," *Management Science*, Vol. 7, No. 2, 1961.

18. Garvey, John J., "The National Shipbuilding Research Program 1971-1976," presented to the Philadelphia Section Society of Naval Architects and Marine Engineers, April, 1976.

19. Geoffrion, A. M., "Lagrangian Relaxation for the Integer Programming," *Mathematical Programming Study 2: Approaches to Integer Programming*, 1975.

20. Geoffrion, A., and R. McBride, "Lagrangian Relaxation Applied to Capacitated Facility Location Problems," *AIIE Transactions*, Vol. 10, 1, 1978.

21. Goldbach, Richard A., "Application of Preoutfitting During Construction of Ammunition Ships AE 32-35," Marine Technology, January, 1973.

22. Graves, R. G., L. F. McGinnis, and L. D. Bailey, "The Outfit Planning Problem," Department of Commerce Contract No. DO-A01-78-00-3074, June 15, 1979.

23. Gross, Donald and Pinkus, Charles E., "Optimal Allocation of Ships to Yards for Regular Overhauls," Technical *Memorandum*, Serial TM-63095, Office of Naval Research, Project NR 347-020, May, 1972.

24. Grubbs, F. E., "Attempts to Validate PERT Statistics of 'Picking on PERT,'" *Operations Research*, Vol. 10, No. 6, 1962, pp. 912-915.

25. Hurst, R., "Some Production Research Activities on Steelwork and Outfitting," The Society of Naval Architects and Marine Engineers, June, 1968.

26. Jolliff, James, V., CDR. USN, "Modular Ship Design Concepts, *Naval Engineers Journal*, Vol. 86, No. 5, October, 1974.

27. Johnson, C., "Scheduling Planning and Reporting Data Information Systems," National Steel and Shipbuilding Company, San Diego, Calif.

28. Karp, R., "On the Computational Complexity of Combinatorial Problems," *Networks*, Vol. 5, 1975.

29. Kelley, J. and M. Walker, "Critical-Path Planning and Scheduling,", *Proceedings of the Eastern Joint Computer Conference*, 1959.

30. Kelley, J. E., Jr., "Critical-Path Planning and Scheduling: Mathematical Basis," *Operations Research*, Vol. 9, pp. 296-320, 1961.

31. Kelley, J. E., "The Critical Path Method: Resources Planning and Scheduling," Industrial Scheduling, J. R. Math and G. L. Thompson, eds., Prentice Hall, 1963.

32. Levy, F. K., G. L. Thompson, and J. D. Weist, "Mathematical Basis of the Critical Path Method," Industrial Scheduling, J. F. Muth and G. L. Thompson, eds., Prentice Hall, 1963.

33. Levy, F. K., G. L. Thompson, and J. D. Weist, "Multi-Ship, Multi-Shop Workload Smoothing Program," Naval Research Logistics Quarterly, Vol. 9, No. 1, 1963.

34. Malcomb, D. G., J. H. Roseboom, C. E. Clark, and W. Fazar, "Application of a Technique for Research and Development Program Evaluation," Operations Research, Vol. 7, pp. 646-669, 1959.

35. McGinnis, L. F., and R. J. Graves, "A Mathematical Model for the Outfit Planning Problem," Department of Commerce Contract No. DO-A01-78-00-3074, October 31, 1979.

36. McGinnis, L. F., and H. L. W. Nuttle, "The Project Coordinator's Problem," OMEGA, Vol. 6, No. 4, 1978.

37. Moder, J. J., and C. R. Phillips, Project Management with CPM and PERT, Reinhold, 1964.

38. Modular Design Applications Study (Deckhouse and Outfit), The U.S. Department of Commerce Maritime Administration, Contract No. MA-4358, PB 178196, 1967, pp. 1-57.

39. Naus, R. M., "An Efficient Algorithm for the 0-1 Knapsack Problem," Management Science, Vol. 23, 1976.

40. Naus, R. M., "The 0-1 Knapsack Problem with Multiple Choice Constraints," University of Missouri-St. Louis, 1976.

41. Padberg, M., and T. Shaftel, "The Modular Design Problem: Convexity of the Constraints Set," Management Science Research Report No. 245, Carnegie-Millon University, March, 1971.

42. Potts, W. R., and W. L. Cuthbert, "L.N.G. Carriers Using the Conch Containment System," The Society of Naval Architects and Marine Engineers, No. 11A, 1975, pp. 21-40.

43. Proceedings for Shipbuilding Industrial/Production Engineering Workshop, R. J. Graves, ed., U.S. Department of Commerce, February, 1978.

44. Sahni, S., and E. Horowitz, "Combinatorial Problems: Reducibility and Approximation," Operations Research, Vol. 26, No. 5, 1978.

45. Scheduling Planning and Reporting Data Information System, National Steel & Shipbuilding Company, San Diego, California.

46. Shaftel, T. L., Thompson, G. L., "A Simplex-Like Algorithm for the Continuous Modular Design Problem," Management Science Research Report No. 248, Carnegie-Mellon University, under contract N00014-67-A-0314-0007 NR 047-048 U.S. Navy Office of Naval Research, January, 1972.

47. Shaftel, T. L., Thompson, G. L., "The Continuous Multiple Modular Design Problem," Management Science Research Report No. 254, Carnegie-Mellon University, under contract N00014-67-A-0314-0007 NR 047-048 with the U.S. Office of Naval Research, January, 1972.

48. Stinson, J. P., E. W. Davis, and B. M. Khumawala, "Multiple Resource-Constrained Scheduling Using Branch and Bound," AIIE Transactions, Vol. 10, No. 3, 1978.

49. Talbot, F. B., and J. H. Patterson, "An Efficient Integer Programming Algorithm with Network Cuts for Solving Resource-Constrained Scheduling Problems, "Management Science, Vol. 24, No. 11, 1978.

50. Weist, J. D., "A Heuristic Model for Scheduling Large Projects with Limited Resources," Management Science, February, 1967.