Scheduling Methods For Ship Build Strategy Development: Literature Search and Research Report

for the

Midterm Sealift Generic Build Strategy Task

by

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16. Abstract

The purpose of this report is to identify existing and evolving scheduling approaches that could be used to help develop and evaluate build strategies for ships. A build strategy embodies and communicates an overall plan for the production of a specific ship, or a contracted series of ships, within a specific shipyard. The primary reasons for developing a build strategy are:

(1) to ensure the particular shipbuilding program is feasible within the constraints imposed by the shipyard, the customer, and the business environment
(2) to provide a framework for the coordination of work both within and across functions in support of the program
(3) to provide a foundation for detailed/tactical operations planning that will generate work packages, material orders, and shop-floor-level work sequences and schedules

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Introduction

The purpose of this report is to identify existing and evolving scheduling approaches that could be used to help develop and evaluate build strategies for ships. A build strategy embodies and communicates an overall plan for the production of a specific ship, or a contracted series of ships, within a specific shipyard.[1][1] The primary reasons for developing a build strategy are:

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This investigation has been premised on the knowledge that world-class shipbuilding is principally a group-technology-based fabrication and assembly process.[2] As such, the efficient operation of a modern shipbuilding enterprise requires that planning and management focus primarily on the aggregate use of resources across all contracts while also satisfying the constraints of specific contracts. Correspondingly, an effective build strategy not only satisfies the constraints of its associated contract, but also, when integrated into the overall operations plan, allows that plan to make efficient use of a shipyard's resources across all anticipated contracts. Such a planning and management approach is fundamentally different from the project-oriented approach that is associated with one-off construction operations. Important characteristics of modern shipbuilding and their implications for planning and scheduling are described in this report.

Within a general manufacturing context, the processes associated with build strategy development and integration are generically part of what is referred to as "medium-range planning."[3][4] And the operations schedule developed as part of the medium-range planning process, representing all work of all contracts in aggregate, is typically called a "master production schedule." This report describes both medium-range planning and prerequisite long-range business planning as generally applied to manufacturing operations. Various scheduling methods are described and evaluated relative to their applicability to build strategy development and master production scheduling within a modern group-technology-based shipbuilding context.

[1] Numbers in brackets refer to references.

Background: Characteristics of Modern Shipbuilding and Their Implications

General Production Approach

A ship will typically have the following general product characteristics:

- extremely large
- very complex
- very high value
- generally produced in low volume (one to ten per shipyard per year)
- made to order
- often at least semicustomized
- a short required contract-to-delivery time relative to its work content

Many of these characteristics might lead one to initially conclude that a craft-based, one-off construction approach is appropriate for producing ships. In fact, this is the production approach that was prevalent throughout the world prior to WW II. However, driven by the urgent need for Allied ships during the war, Kaiser and Hann recognized that the principles of group technology (GT) could be applied to shipbuilding.[5][6] This recognition was facilitated by the evolution of welding technology and by Kaiser's and Hann's experiences within other industries.

The GT-based approach dictates that ships can be progressively subdivided into intermediate or interim products that can be classified into groups or "families" based upon commonality of production process. An interim product is any physical subdivision of a product that objectifies a discrete set of work. The production process for each interim product group can be rationalized to eliminate unnecessary tasks and to efficiently utilize focused resources, sometimes resulting in a dedicated work cell or process lane. Each of these focused processes can then be used repetitively on many similar interim products, resulting in significant economies of scale at the interim product level. Also, using this approach, interim products of different types can be produced in parallel and then assembled at later stages, greatly reducing overall production cycle time.

World class shipbuilders have demonstrated that significant benefits can be realized from GT even when concurrently building ships that vary somewhat in type, size, technology, and detail, as there is still much similarity amongst their interim products throughout all stages of production. Obviously, the more standard these ships are, the more focused and dedicated the shipyard's production processes and tools can be, and the greater the potential gains. However, GT requires that interim products be only similar enough to have common production processes. In fact, the potential gains from increased standardization are very small relative to the gains associated with initially just moving from a traditional construction-oriented approach to a GT approach. The potential marginal gains from increased product and process standardization must also be weighed against the resulting loss of business flexibility/agility and product marketability over time.

Implication: The medium-range planning process used must be appropriate for very large, complex, high-value, low-volume, semicustom products that are made to order in a short time frame using a group-technology-based production approach.

Ship's Product Structure Characteristics

The process of building a ship can generally be represented by a hierarchical A-type product structure, as shown in figure 1.[7] In such a process, parts are manufactured and components are purchased, and these parts, components, and subsequent interim products are progressively assembled to eventually form a single product. Such an assembly-based production process has dependent demand, as each interim product depends on manufactured parts, purchased components, and/or subassemblies from lower levels in the product structure.

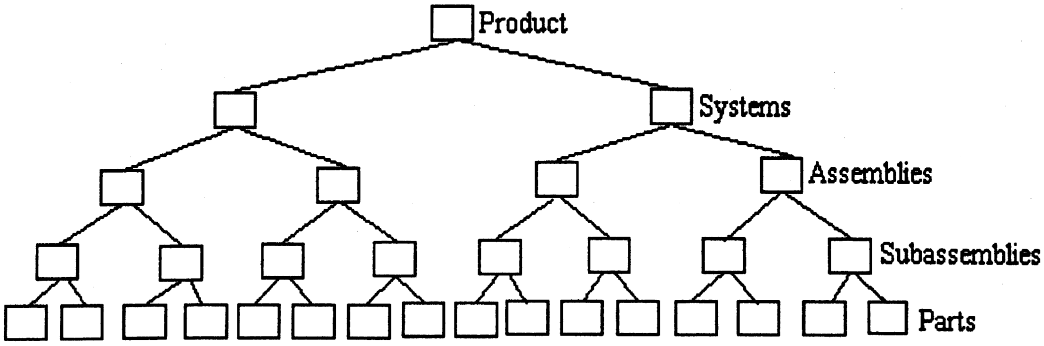

Figure 1. Generic A-Type Product Structure.

A ship's product structure is not a pure hierarchical A-type structure, however, because some many-to-many relationships exist between certain types of high-level ship interim products, as shown in figure 2. Particularly, at the block/assembly-to-zone level of a ship's product structure, the erection of a single block or major assembly can play a part in the creation of several on-board outfitting zones, and a single on-board outfitting zone is likely to have been created by the erection of more than one block or assembly. Similarly, at the zone-to-ship system level, on-board outfitting work in a single zone can be prerequisite to the completion and testing of several ship systems, and a single system can be present in several zones.

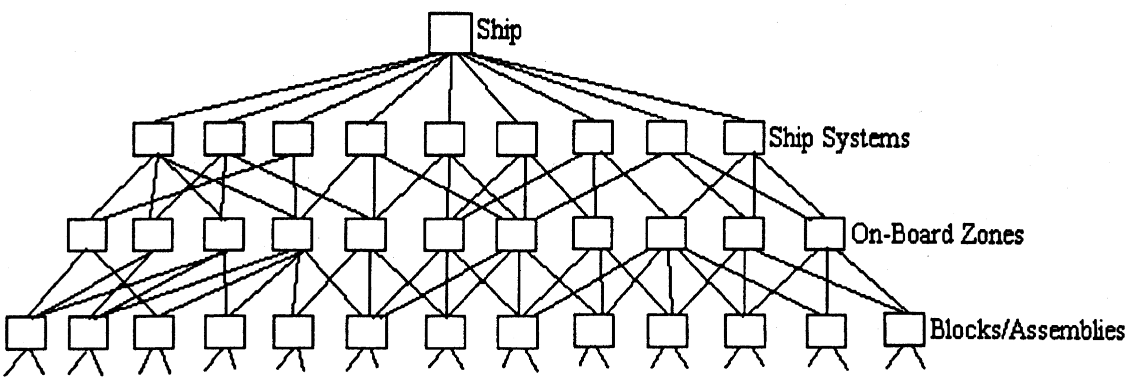

Figure 2. Many-To-Many Relationships In Upper Levels of a Ship's Product Structure.

Implication: The medium-range planning process used must account for dependent demand. Also, because the medium-range planning process uses the interim products in the upper levels of a ship's product structure to derive the ship's work, it must be able to account for the many-to-many relationships that exist there.

Operations Management Orientation

Because there are typically many interim products of several ships continually competing for the finite capacity of a shipyard's resources, planning for and managing such an operation solely from the ship/contract/project perspective, as would be done within a traditional construction context, will result in competing, uncoordinated, and erratic demand on individual production resources. This, in turn, will result in tremendous inefficiency, delays, disruption costs, and work-in-process (WIP) inventory costs. Therefore, the primary operations planning and management task is to optimize process/resource utilization for interim products across all contracts in aggregate.

However, because of the high value of each ship, owners/buyers with a project focus have and exercise significant power over shipyards. Also, because shipyard cash flow is usually tied to key project-specific milestones, significant attention should be paid to the potential financial implications of project-specific planning decisions. So managing such an operation solely from a aggregate perspective could result in late ship deliveries and/or lost financial opportunities.

Implications: The medium-range planning process used must be able to simultaneously address aggregate resource and material issues, and project/ship-specific dependent demand, work criticality, contract milestones, and delivery schedule constraints.

System Variability

Variability In Process Performance - Significant levels of performance variability will occur in shipyards that have not fully or effectively established GT-based interim product families and associated processes, or implemented SQC/SPC procedures throughout operations to maintain and improve process control. This performance variability and its accumulation through a ship's many stages of interim product concatenation can have a major impact on overall production system predictability and performance, and associated cost and schedule risk.[8]

Variability In Demand - Demand for a shipyard's products and capacity can be difficult to predict. For planning purposes, demand can be dealt with either deterministically or stochastically depending on the circumstances. If there is no uncertainty about demand for the shipyard's capacity over the medium-range planning time horizon, the planning problem is deterministic. This would likely be the case if a shipyard includes only current work and highly probable proposed work in its medium-range planning process.

If the medium-range planning process includes ships that have only been forecast, stochastic representation of at least some of the forecast demand may be necessary depending the length of the planning horizon, the reliability of forecasts, the overall size of the product's market and the level of competition in that market. Following are two examples of using deterministic versus stochastic data in planning.

> Example 1: A shipyard has the capacity to competitively produce four ships of a particular type per year, and knows that there are three competitors that can do the same. The medium-range forecast identifies total demand ranging from 10 to 15 of these ships in each of the next two years, with 11 ships per year being most likely. In this case, the stochastic nature of this forecast is very important for this shipyard's planning. Conversely, if the medium-range forecast identifies an expected demand of 15 to 20 of these ships in each of the next two years, the

shipyard can probably use a deterministic planning approach that assumes a steady demand of four ships per year.

Example 2: A shipyard is competing for two independent contracts for which the start dates are known. The probability of winning contract A is determined to be 95%, while the probability of winning contract B is determined to be 50%. In this case, planning should probably treat contract A deterministically and contract B stochastically.

Implications: The medium-range planning process should be able to account for process variability through stochastic representation of associated variables, and also should be able to employ a stochastic representation of demand if necessary. When stochastic representations of process performance and/or demand are used, the medium-range planning process should generate probabilistic schedules, resource utilization plans, and cost estimates, , both for risk assessment and to support the development and inclusion of risk mitigation strategies as part of the overall build strategy.[2] *The goal of stochastic planning is to generate a plan that has a probability of occurrence that is acceptable from the standpoint of satisfying both the customers' needs and the company's strategy and business plans; that is, that represents acceptable levels of business risk for the company and its customers.*

Degree of Individual Product Uniqueness

Some commercial ship market segments, like the bulk carrier segment, are primarily commodity-like, while other market segments, like the cruise ships segment, are made up almost entirely of semicustom or custom ships. Most commercial ship market segments, however, have a low-end, commodity-like subsegment and a higher-end, semicustom or custom subsegment.

Within a commodity segment or subsegment, ships have essentially equivalent features and capabilities, and price and contract-to-delivery cycle time are the only significant marketing characteristics. In a commodity market, producers who want business are forced to accept the price and cycle time performance set by the price/performance leaders with available production capacity.[3] Because of the resulting price and performance pressure, profit per unit of production is usually very small. So commodity producers attempt to earn acceptable profit levels and improve performance by increasing production capacity and volume, that is, market share. This, in turn, adds even more price and performance pressure to this market. Poorer performing producers can not profitably compete in commodity markets unless demand is so high that the capacity of all the better performing producers in that market is fully utilized.

Within higher-end market segment or subsegments, customers are looking for added value along a number of additional product dimensions, including:

- improved financing
- reduced *concept*-to-delivery cycle times
- higher quality
- improved functional and qualitative features

[2] "Simulation" in this instance refers to Monte Carlo-type simulation.

[3] Price and cost in this context include the effects of any relevant subsidies.

- improved technology
- lower operations costs, including costs associated with normal operations, reliability, maintenance, and overhaul
- increased life cycle support

Identifying and meeting customer needs in higher-end market segments requires a great deal more work in marketing, product development, and planning. But the potential rewards are great as the shipbuilder can then set its prices according to each unique ship's perceived differentiated value.[9]

Implications: Because of the narrow profit margins and strict delivery requirements associated with commodity ships, scheduling and cost estimating in support of commodity shipbuilding must be extremely accurate. Also, because of the commonality of such ships, much of the up-front design and planning work is complete at contract award and the vast majority of the contract-to-delivery time and cost is associated with material control and production. So medium-range planning will be focused on these aspects of operations with fairly complete design information and planning standards being available. For semicustom and custom ships, a significantly larger portion of contract-to-delivery time and cost will be associated with product development, design, engineering, material procurement, and planning. Therefore, the medium-range planning process for such ships must be much broader in scope and focused on overall coordination of work associated with all important product dimensions. This planning process must also be able to deal with incomplete and evolving information.

Similar Industries

Other moderate volume producers of complex, high-value, assembled products include the aerospace, heavy-equipment, large-machinery, and large-machine-tool industries. Ships will typically have a higher level of work content and complexity and a lower level of product and interim product standardization than the products of these other industries, with some specific exceptions. Shipbuilding has also sometimes been compared to large-scale industrial plant and building construction. But while some large-scale construction enterprises utilize a GT-based approach for some fabrication and subassembly work at dedicated off-site facilities, industrial plant and building production work is still planned and managed primarily as project-oriented, on-site construction.

Implications: Shipbuilding has much in common with other manufacturing industries, particularly when viewed in a GT-based context. Therefore, much can probably be learned and applied from the existing body of knowledge in general manufacturing, operations management, and production planning.

Description of Long-Range and Medium-Range Manufacturing Planning Processes

Following is an overview of how manufacturing companies typically develop long-range and medium-range operations plans and schedules. Figure 3 shows the outputs of these planning processes and their relationships. This overview summarizes these processes as they are presented in current operations management and production planning literature.[10][11]

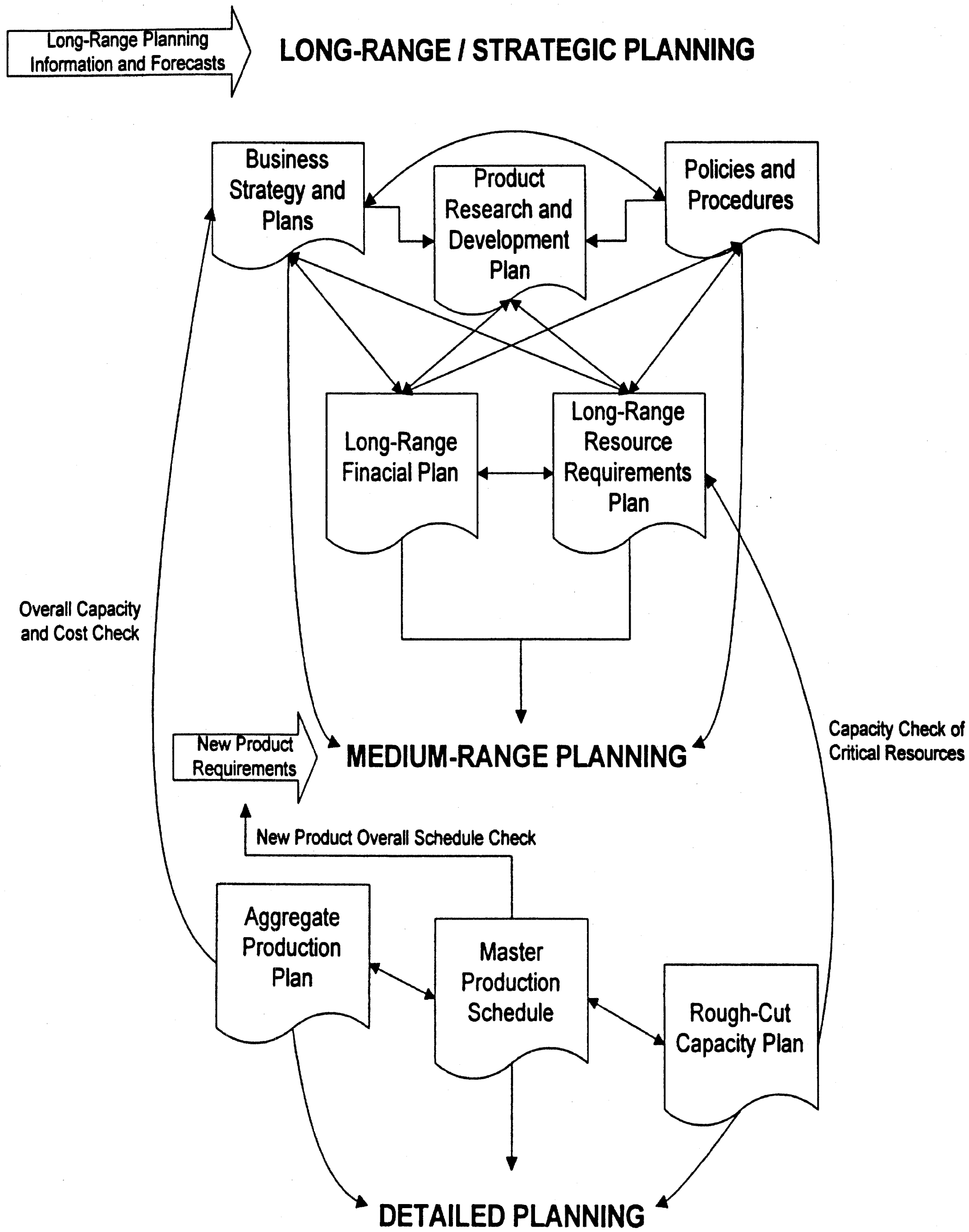

Figure 3. Typical Long-Range and Medium-Range Manufacturing Planning Process.

The Long-Range / Strategic Planning Process

A business will typically carry out long-range planning annually, or when the business environment changes significantly, using the current status and long-range projections for each of the following:

- general macroeconomic climate
- market demand for product(s)
- money markets
- human resource markets
- capital goods markets (hard technologies)
- subcontractor markets
- raw material and purchased component markets
- political environment
- the company's capabilities and backlog
- potential competitors' expected backlogs, capabilities and actions

Long-range planning can have a ten-year time horizon with planning considered in one-year increments or "time buckets," although this can vary significantly by product type. For instance, long-range planning in the computer industry usually has a time horizon of three years or less because of the pace of associated technological change. Long-range planning outputs typically include the following items:

- a *business strategy* that articulates product lines, organizational structure, quality goals, pricing goals, delivery and service level goals, market-share and production-volume goals, profitability goals, etc. over the planning horizon
- business *policies and procedures* that, within the context of the overall business strategy, represent process and product standards for marketing, design, operations, finance, purchasing, logistics, human resources, and cross-functional activities
- a *resource-requirements-and-capacity plan* that identifies the capacity and associated facilities, equipment, personnel, and subcontractor and supplier relationships that will be required to meet the long-range goals identified in the business strategy
- a *product research-and-development plan* to meet the perceived needs of the market as articulated in the business strategy
- a *financial plan* that describes the approaches to the money markets and share holders that will be used to support the business strategy, the long-range resource-requirements-and-capacity plan, and the long-range product-development plan

The Medium-Range Planning Process

Medium-range plans are typically revised monthly or quarterly, or as the business situation changes, using the long-range plans as a point of departure. Medium-range planning typically has a time horizon of 12 to 60 months, and time buckets of anywhere from a day to a month, depending on product type and complexity, typical production cycle time, demand forecast variability, and the associated level of risk the company is willing to accept. Medium-range plans account for all certain work and can also include proposed and forecast work. The medium-range planning process and associated build strategies will be constrained by the shipyard's business strategy, long-range business plans, operations policies and procedures, capabilities and capacities, and anticipated concurrent work, customer requirements, the cost of capital, ships' characteristics, and the anticipated availability of material, components, and associated information. Medium-range planning typically results in the creation of the following outputs.

- An *aggregate production plan (APP)* specifies total projected aggregate demand and output either per time bucket or cumulatively over time. It is developed to identify the overall resource and inventory utilization strategy that is most likely to minimize total operations costs over the planning period while satisfying the service/delivery, quality, and overall production volume goals defined in the long-range plan. Such a strategy will seek to minimize cost over the planning horizon by varying the relative use of in-house production capacity, inventory/backlogging, and subcontracting to satisfy overall demand. Total aggregate demand and output are expressed by a surrogate attribute common to all products, like direct labor hours, units of production, or tons. At one extreme, the APP could reflect a "chase" strategy where in-house capacity/output is varied continually over time to exactly match expected aggregate demand. At the other extreme, the APP could reflect a constant capacity strategy where incremental demand greater than this capacity would be handled with overtime or subcontracting, and/or worked earlier at times when demand is less than capacity and then stored in inventory. Nearly all real-life APP strategies fall somewhere between these two extremes. Reference [10] presents an excellent APP example. Various methods are used to develop APPs including manual iteration called "cut and try," mathematical modeling, computer-based heuristic modeling, and simulation of *master production schedules* (see below).

- A *master production schedule (MPS)* specifies dates and quantities of production for each specific product, or for each of a number of common upper level interim products (called "end items" or "planning units") for complex products, within the constraints of the APP. The MPS serves as the basis for ensuring and reserving adequate capacity of critical production resources over time for all work to be accomplished (see "rough-cut capacity plan" below), generating detailed ("shop floor") production plans and schedules, and establishing a material procurement schedule. Other inputs to the MPS include the structured bills of material for all products down to the planning unit interim product level (for the identification of planning units and their associated dependencies), and the process standards documented in the company's policies and procedures (used for the identification of work breakdown structures, process durations, and resource requirements for each type of product or planning unit).

- A *rough-cut capacity plan (RCP)* identifies the expected usage of critical resources over time for all products or planning units in support of the MPS. The RCP is compared to the long-range resource requirements and capacity plan to assure that adequate resources will be available within the medium-range time horizon. If it is determined that the long-range resource requirements and capacity plan does not support the critical resource needs dictated by the MPS, management can modify the long-range resource-requirements-and-capacity plan, the APP, and/or the MPS. Note that any changes to the long-range resource-requirements-and-capacity plan will likely require changes in the other long-range and medium-range plans.

Planning For A New Product

When a new product is proposed for production, the management team must first determine if the product fits within its business strategy, existing policies and procedures, and its other long-range plans. If the product obviously does not fit, management must either drop the product from consideration or modify the organization's long-range plans.

If the product clears the initial strategic hurdle, a new iteration of the APP is generated including the new product and any additional copies that customers will desire. In doing this, the overall capacity reservations over time for all previously committed/ contracted products can be changed as long as their critical schedule milestones are not altered. The regenerated APP should provide a good overall indication of:

- the new product's overall production duration
- the overall capacity, overtime, subcontracting and inventory requirements that will most economically satisfy aggregate demand for all products, including the new product, through the medium-range planning horizon
- whether the initial new product can be produced within the required time constraint
- whether follow copies of the new product can be delivered at the desired rate

If there are overall capacity problems identified at this point, the company may not be able to produce the product. Or the long-range plans might be revisited to see if changes might be made to profitably accommodate the product.

If the product makes it past the APP hurdle, the MPS and RCP are generated to include the new product. The MPS must support the APP, and the RCP must not exceed the key resource limitations designated in the long-range resource-requirements-and capacity-plan. The MPS will identify times and quantities of production for each planning unit while also accounting for the capacity constraints of specific resource and intraproduct dependent demand. The RCP will identify the utilization levels of key resources over time across all products. The new product's production schedule and critical-resource-utilization plans can be extracted from the MPS and the RCP, respectively, at the planning unit level. Because the APP, MPS, and RCP are so interrelated, they evolve in an integrated and interactive way. Once again, the overall objective of this planning process is to minimize business risk and improve the probability of meeting the goals of the shipyard and its customers.

Literature Search Results

The literature search was conducted to identify medium-range scheduling methods and tools that are being used today in manufacturing environments similar to shipbuilding, and also methods that are being researched and developed for potential future application in these environments. Following are brief descriptions of the general methods that have been identified. It is beyond the scope of this report to describe these methods in detail and provide working examples, so the reader is referred to the references for more detailed descriptions and information.

Search-Based Heuristics

Some simple heuristics have been shown to find optimum product sequencing solutions for some very simple independent-demand job-shop and flow-shop production systems (like n jobs of known duration and one machine, and n jobs of known duration and two machines in sequence). Examples of these heuristics include first come first serve, earliest due date first, shortest processing time first, longest processing time first, least slack first, etc. These types of heuristics are not adequate by themselves for finding useful solutions for more complex medium-range planning problems. However, such heuristics can sometimes be useful for determining near-optimum work sequences and schedules when used in combination and/or with other scheduling approaches. Search-based heuristic methods, like branch-and-bound and branch-and-cut, are methods for utilizing rules to narrow the solution space of a combinatorial optimization problem so as to efficiently obtaining a "good" solution. There is at least one know application of this approach to medium-range planning and scheduling of ship production in Korea.[12][13][14][15][16][17][18]

Mathematical Modeling

Mathematical modeling generally involves the optimization of one or more objectives that are represented mathematically (e.g., "maximize profit") subject to a set of constraints that are also represented mathematically (e.g., panel line usage <= panel line capacity of 3000 hours/year). Common approaches of mathematical modeling are linear, integer and nonlinear programming, goal programming for multiple objectives, and dynamic programming for such problems solved over time. These techniques were developed in the 1950s, and are commonly used for capacity planning and scheduling in continuous processing industries like oil refining, steel, chemicals, and paper manufacturing, and in assembly, transportation, and service industries. The outputs of these methods will typically include sensitivity analyses of input variables for risk assessment. Although mathematical models are generally intuitive, a high level of competence is required for their development and use in real-world situations.[19][20][21][22]

Network Scheduling

Network scheduling generally represents the critical path method (CPM), program evaluation and review technique (PERT), graphic evaluation and review technique (GERT), and probabilistic network evaluation technique (PNET). Network scheduling is typically project focused, represents work via each project's networked work breakdown structure (WBS) tasks, backward and forward schedules the project tasks, and identifies the project's critical tasks and path, and the slack or float on other tasks. Most network scheduling software packages support the identification of resources and material to tasks, and thus allow the generation of resource and material constrained project schedules, as well as utilization plans for the resources and material themselves. These packages also generally support the identification of costs to resources so that cost estimates can be generated integrally with schedules and resource utilization plans. Some approaches support the simultaneous scheduling of multiple projects sharing a common pool of resources, and some support stochastic representation of task durations and costs, thus allowing probabilistic schedule simulation for the assessment of schedule and cost risk. Network scheduling is probably the scheduling approach that is most familiar to U.S. shipbuilders, although it is not clear that these shipyards utilize all of this method's capabilities.[23][24][25][26][27][28] [29][30][31][32][33]

<u>BOM-Based Backward Scheduling With Standard Lead Times</u>

This approach generally represents the material requirements planning (MRP) methodology in which work is represented by hierarchically structured bills of material for dependent-demand assembled products, together with associated standard production lead times for each interim product. Interim products are backward scheduled down the legs of the product structures from their final products' or end items' due dates using the standard lead times. This methodology has continually been refined ("closed-loop" MRP, MRP II, ERP) to account for finite capacity and nonhierarchical substructures (many-to-many relationships) in the BOM, and to more efficiently schedule all resources relative to aggregated product demand. This approach was developed by IBM in the mid-1960s along with hierarchical database technology, and is information system intensive. Some U.S. shipyards have attempted to use an MRP-type approach for detailed-level planning and scheduling.[34][35][36][37]

<u>Synchronous Manufacturing Scheduling</u>

This approach is based on what is commonly known as the theory of constraints. It focuses on identifying the bottleneck resource in the process, "exploiting" that constraint to the greatest extent possible (finding ways to maximize its throughput in support of demand), and then "subordinating" all other processes to the "drumbeat" of the bottleneck. Work is sequenced at the bottleneck to support final demand. Then dates for release of material from the bottom of the product structure into the production process are backward scheduled from the bottleneck's requirements using the length of "time buffers" between release and the bottleneck, at the bottleneck itself, and between the bottleneck and final product delivery. These time buffers will include setup time, process time, queue time, wait time, and idle time. Capacity is accounted for explicitly at each step in the scheduling process. Strict heuristics establish priorities for job sequencing at the bottleneck (earliest due date first) and for increasing throughput at resources that are not bottlenecks but that are temporarily constrained: (1) batch products if possible to reduce setups (increasing WIP), (2) use overtime specifically for critical jobs, (3) off-load critical jobs to other resources, (4) delay final product delivery. This approach has tended to be more of a philosophy than a formal methodology because of the lack of objective documentation of the methodology and its implementation in industry. Most U.S. shipyards are familiar with, and agree with, the fundamental ideas articulated by the theory of constraints.[38][39][40][41]

Discrete Events Simulation

This approach models the production process as a complex set of interrelated discrete events that occur through time. Within a simulation model, production resources, material handling entities, product/interim product entities, and information entities are modeled and their logical relationships defined. Each entity includes the definition of specific attributes that will impact system performance. Production is simulated by the product entities actually going through the discrete events of production in time simulated by the computer's clock. Many entity characteristics can be represented either deterministically or stochastically, and probabilistic results can be obtained. Discrete events simulation tools do not normally incorporate work sequencing and scheduling functions, so simulation by itself cannot be considered a scheduling approach. Therefore, for scheduling purposes, it must be combined with other methodologies (see "Agent-Based Systems" below), and really serves as both a tool for validating a given schedule within the production system, and potentially as a graphic user interface. A significant level of expertise is required to build, run, and interpret realistic simulation models, although simulation systems are evolving to include more intuitive interfaces and standard libraries of common servers and other entities. Many U.S. shipyards are familiar with discrete events simulation primarily from a process design perspective rather than a planning and scheduling perspective. However, at least one U.S. shipyard has successfully incorporated discrete events simulation into detailed shop-floor-level scheduling of its panel line.[42][43][44]

Expert Systems

An expert system is a set of hierarchical heuristics or rules that infer the actions and interactions of objects in a specific domain with the objective of making a particular decision in that domain. Expert systems are useful for solving problems in domains where qualitative issues must be addressed. The logic within an expert system is structured and is often based on the "rules of thumb" that an "expert" has derived through experience to get "good" workable solutions to a specific problem. The concept of expert systems is known to some U.S. shipyard. [45][46][47][48]

Agent-Based Systems

An agent-based system is also a heuristic system. However, rule sets are embodied in the objects within the system that interact to attempt to accomplish certain goals. Each object's rules dictate how that object will react to encounters with, and the actions of, other agents and the environment. The rules that govern an agent's behavior may also change according to its interactions. Current agent-based scheduling systems are implemented within a discrete-events-simulation framework. This approach to heuristic-based system modeling is much less structured than an expert system, and is thus more flexible. In many respects, this approach resembles real-life domains where people, objects, and information interact, negotiate, make decisions, and solve problems simultaneously according to individual and global needs and the conditions of the domain at that time. Agent-based applications to planning and scheduling are relatively new to all industries, but there are some relevant references available.[49][50][51]

Systems Dynamics Simulation

Also known as numerical simulation, systems dynamics is an approach that attempts to identify and characterize mathematically all of the interactions between objects and activities in a particular system, and then identify how certain specific changes to the system will propagate and impact the individual elements of the system and the system as a whole. Its focus is on the prediction of impacts from system changes, or contingency planning, not necessarily initial planning. The objective is similar to agent-based systems, except in this case the system's behavior is described mathematically rather than heuristically. Decision Dynamics, Inc. has done some work in applying systems dynamics to predicting outcomes of changes in ship production scenarios. Some of the shipyards in this project have beta tested DDI's software.[52][53]

Evaluation of Medium-Range Master Scheduling Methods

Following is a general evaluation of the applicability of the scheduling methods identified above to the ship production domain. This evaluation criteria were developed by UMTRI-MSD based on the perceived needs of U.S. shipyards and the Navy, and were reviewed by the BSM team and modified as necessary. UMTRI-MSD then evaluated the various methods versus these criteria. Following the descriptions of the criteria, an Evaluation Results Matrix is provided along with an Evaluation Summary and Recommendations.

Evaluation Criteria

- Easy to Understand and Use
  Identifies whether a typical production planner within a US shipyard would find a particular method easy to comprehend and associated scheduling models easy to build. "Yes," "Somewhat," "No."

- Familiar to US Shipbuilders
  Measured in degree. "Yes," "Somewhat," "No."

- Addresses Finite Capacity / Resource-Constraints
  Simply identifies whether the method always assumes infinite capacity, or whether it supports finite capacity or resource-constrained scheduling, including resource leveling. "Yes" or "No."

- Allows for Different Dependency Types Between Tasks or Interim Products
  Sometimes the performance of a dependent task is not constrained only by the finish of other tasks (finish-to-start constraint, FS). Sometimes start-to-start (SS), start-to-finish (SF), and finish-to-finish (FF) constraints more realistically represent the interdependencies between some tasks. For example, the testing of a particular ship system may be able to start after the assembly of its first outfit unit, but cannot be finished until some period of time (lag) after its last outfit unit is erected and related on-board outfitting work in that zone is finished. This identifies whether a particular method allows the use of these different types of dependencies and their associated lag times. "Yes" or "No."

- Allows the Use of Heuristics for Task Prioritization
  Sometimes there may be other factors that should influence scheduling that can be expressed by heuristics. For example, if two flat blocks are scheduled to start assembly at exactly the same time but there is only one flat block assembly bay available, a heuristic might state that the block with the least total project slack has priority. Another example: one might want particular tasks to start as late as possible without influencing the completion date of the project to support a just-in-time operations policy. This measure identifies whether a particular method allows for the use of user-defined heuristics beyond the intraproduct dependencies described above. "Yes" or "No."

- Performs Forward and Backward Scheduling to Identify Critical Paths and Tasks
  Forward and backward scheduling establishes time windows in which each specific task can be scheduled without impacting overall project/ship schedules. This capability can provide information about task float or slack, critical tasks, and schedule flexibility that management can use to make tradeoffs relative to resource utilization, inventories, material procurement, cash flow, risk, etc. "Yes" or "No."

- Provides Aggregate Resource Management Perspective
  Planners and managers are able to review the schedules and utilization of key resources (human and capital) across all ship contracts, and identify and manipulate tasks within any project and resources that are constrained or critical in order to facilitate improved aggregate resource management and efficiency. "Yes" or "No."

- Provides Project/Contract Management Perspective
  Planners and managers are able to review work schedules for individual projects/ship contracts, identify and manipulate those tasks that are critical, and keep track of key project dates to facilitate improved project/contract management. "Yes" or "No."

- Provides Material Management Perspective
  Planners and managers are able to review material schedules across all ship contracts and identify if and where there are potential material procurement problems for improving material management. "Yes" or "No."

- Supports Easy and Fast Scenario Analyses ("What if...")
  Changes to inputs and constraints are easy to make, and alternative schedule scenarios can be created, analyzed, and compared quickly. "Yes" or "No."

- Provides Optimization Capability
  The approach has a means of iteratively revising and improving the schedule relative to specified objectives. Such capability can be implemented through the use of such things as genetic algorithms and search-based heuristic methods. "Yes" or "No."

- Determines Realistic Impacts of Potential Work-In-Progress Changes
  The impact of plan changes during the production process is typically nonlinear. For example, the addition of work during production will not simply result in the addition of that work's labor hours and time to the existing plan because of disruption and the replanning required to make the best use of resources within the changed constraints. While analyzing the impact of in-process changes may not be part of medium-range planning for some, others may want to carry out realistic contingency planning at this stage. "Yes" or "No."

- Provides Risk Analysis Capability
  Supports schedule risk assessment through the determination of probabilistic outcomes based on stochastic inputs and/or sensitivity analysis of inputs. "Yes" or "No."

- Commercial Software Available
  Identifies whether there is commercially available software that supports a particular method. "Yes" or "No."

- Software Easily Integrates With Other Planning Tasks
  If software is commercially available to support a particular method, it can be easily integrated with front-end processes and their applications, such as a structured BOM and process definition standards, other medium-term processes and their applications, such as task duration calculation, APP, RCP, and RCP versus Long-Range-Resource-Requirements-and-Capacity Plan comparison, and follow tasks such as report generation, long-lead-time material procurement, and detailed shop-floor planning and scheduling. "Yes," "Somewhat," "No."

Evaluation Results Matrix

Evaluation Criteria -	Easy to understand and create scheduling models	Familiar to US shipbuilders	Addresses finite capacity / resource constraints	Allows different dependency types between tasks	Allows the use of heuristics for task prioritization	Identifies critical paths and tasks	Provides resource management perspective	Provides project / contract management perspective	Provides material management perspective	Supports easy and fast scenario analyses	Has Optimization Capability	Can determine realistic impacts of changes	Has risk analysis capability	Scheduling-specific software is available	Software easily integrates with other planning tasks
Medium-Range Scheduling Approaches															
Heuristics	S	S	Y	Y	Y	N	Y	Y	N	N	Y	N	N	N	N
Mathematical Modeling	N	S	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	N
Network Scheduling	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	S
BOM-Based Scheduling w/ Std. Lead Times	Y	Y	Y	N	Y	N	Y	N	Y	Y	N	N	N	Y	Y
Synchronous Manufacturing Scheduling	S	S	Y	Y	N	N	Y	Y	Y	N	N	N	N	Y	?
Discrete Events Simulation	S	S	Y	Y	Y	N	Y	N	Y	N	N	Y	Y	N	S
Expert Systems	S	S	Y	Y	Y	N	Y	Y	Y	Y	N	N	N	N	S
Agent-Based Systems	?	N	Y	Y	Y	?	Y	Y	Y	Y	Y	Y	?	Y	?
Systems Dynamics Simulation	S	S	Y	N	Y	N	Y	Y	N	Y	N	Y	N	N	S

Evaluation Summary and Recommendations

In the short term, all the capabilities of the network scheduling approach should be utilized to accomplish the master production scheduling process necessary for build strategy development. This approach is the most familiar to U.S. shipbuilders and supports much of the required functionality. A full-featured network scheduling application like Primavera should be used. In addition, associated research and development should be carried out in the areas of schedule optimization, realistic contingency analysis (perhaps through integration with systems dynamics simulation), realistic risk analysis, and integration with other planning functions.

Also in the short term, the heuristic scheduling approach described by Lee et. al. [13] should be implemented in a generalized form. Research and development in the areas of realistic contingency analysis, risk analysis, and integration with other planning functions should also be carried out in support of this approach. Once developed, it could be benchmarked against the network scheduling methodology for ease of use and usefulness.

In the medium term, the applicability of an agent-based approach to master production scheduling should be investigated because of its potential for accurately emulating real-world planning operations and providing inherently realistic and useful results. This approach would be implemented with a discrete-event-simulation interface.

In spite of its significant capabilities, mathematical modeling is not likely to be implemented within some shipyards because developing, implementing, and understanding useful models is difficult.

Although BOM-based scheduling with standard lead times was specifically developed to deal with dependent-demand assembled products in aggregate, it typically assumes that only finish-to-start constraints exist between interim products in different levels of the product structure. This method also sometimes has difficulty with many-to-many relationships within the product structure. Only backward schedules are produced by this method and thus it does not provide information about project-specific critical tasks and paths. The method also typically assumes that lead times are deterministic, thus preventing risk analysis. While software developers have continued to refine this approach to attempt to address some of these problems, it is probably not the best approach for master production scheduling. However, it might still represent the best way to "explode" the master production schedule down into more detailed shop-floor plans and schedules, as identified by Neumann.[32]

Synchronous manufacturing scheduling is too undefined in the literature at this point to determine its usefulness for master production scheduling. Goldratt makes some broad generalizations in outlining this scheduling approach that practitioners continue to question. For example, he suggests that the first strategy for increasing the capacity of a temporarily constrained resource is always to increase batch size, thus increasing WIP, when other strategies, such as temporarily adding overtime, might have more economic merit in some circumstances. There is software available that purports to use this methodology for shop-floor level scheduling. Perhaps this software could be obtained and exercised to ascertain its potential validity and usefulness for medium-range planning.

Discrete-events simulation by itself has no inherent scheduling capability, so it must be interfaced with some other sequencing and dispatching tools. It is also not capable of identifying critical paths and tasks and thus providing a project management perspective. Its best potential use with respect to master production scheduling might be to serve as a validation tool and interface for an agent-based scheduling system.

An expert system is made up of a structured hierarchical set of heuristics that have been found to produce "good" and useful solutions for a particular domain. If a particular expert system is applied to a domain for which it was not intended, it will not produce useful solutions. Because U.S. shipbuilders are likely to produce a variety of products, and because yards vary considerably in their capabilities, it is not likely that a single expert system can be developed as the master production scheduling tool for all potential shipbuilding situations.

Systems-dynamics simulation is best used for analyzing the impact of changes to a system based on empirically developed relationships between system entities. In this regard, it might be most useful for scenario analysis and optimization when used in conjunction with other scheduling approaches, rather than for initial system modeling.

References

Book titles are underlined, technical report, journal and proceedings titles are italicized, and paper titles are in quotes.

[1] Lamb, T., *Build Strategy Development*, National Shipbuilding Research Program, NSRP 0406, 1994.

[2] Storch, R. L., Hammon, C. P., Bunch, H. M., and Moore, R. C., Ship Production, Second Edition, Cornell Maritime Press, Centreville, MD, 1996, pp. 45-53.

[3] Chase, R. and Aquilano, N., Production and Operations Management - A Life Cycle Approach, Sixth Edition, Richard D. Irwin, Inc., Homewood, IL, 1992, pp. 608-611.

[4] Narasimhan, S., McLeavey, D., Billington, P., Production Planning and Inventory Control, Second Edition, Prentice Hall Inc., Englewood Cliffs, NJ, 1995, pp. 251-253.

[5] Chirillo, L. and Chirillo, R., "The History of Modern Shipbuilding Methods: The U.S.-Japan Interchange," *Journal of Ship Production*, Vol. 1 No. 1, February 1985.

[6] Storch, R. L., Hammon, C. P., Bunch, H. M., and Moore, R. C., op. cit., pp. 163.

[7] Chase, R. and Aquilano, N., op. cit., pp. 931-936.

[8] Storch et. al., Process Analysis Via Accuracy Control, Revised, USDOT Maritime Administration and Todd Pacific Shipyards Corporation, 1985.

[9] Corey, R., Industrial Marketing - Cases and Concepts, Fourth Edition, Prentice Hall Inc., Englewood Cliffs, NJ, 1991, pp. 7.

[10] Chase, R. and Aquilano, N., op. cit., pp. 607-633.

[11] Narasimhan, S., McLeavey, D., Billington, P., op. cit., pp. 255-284, 302-335, 399-415.

[12] Ibid., pp. 282, 485-496.

[13] Lee, T.E., Song, J.S., Im, J.C., Park, J.C., Jeong, D.S., and Lee, K.R., "Search-Based Heuristic Algorithms for Basic Planning in a Large Shipyard," *Journal of Ship Production*, Vol. 12, No. 4, Nov. 1996, pp. 211-219.

[14] Pinedo, M., Scheduling Theory, Algorithms, and Systems, Prentice-Hall, Englewood Cliffs, NJ, 1995.

[15] Bhattacharya, S., Production Planning and Control: An Integrated Approach, Vikas Publishing House PVT Ltd. New Delhi, 1986, pp. 106-111.

[16] Mellichamp, J.M., and Love, R.M., "Production Switching Heuristics for the Aggregate Planning Problem," *Management Science*, Vol. 24, No. 12, August 1978.

[17] Minton, S., and Philips, A.B., "Applying a Heuristic Repair Method to the Hubble Space Telescope Scheduling Problem," *Innovative Approaches to Planning, Scheduling and Control. Proceedings.*, Nov. 1990, pp. 215-219.

[18] Baker, E., Bodin, L., Finnegan, W., and Ponder, R., "Efficient Heuristic Solution to an Airline Crew Scheduling Problem, *AIIE Transactions*, Vol.11, June 1979.

[19] Chase, R. and Aquilano, N., op. cit., pp. 395-441, 629-632.

[20] Narasimhan, S., McLeavey, D., Billington, P., op. cit., pp. 272-279, 329-331.

[21] An Integrated Approach in Production Planning and Scheduling, Springer-Verlag, 1983, pp. I.1-I.4.3.

[22] Keith, E.G., "Operator Scheduling," *AIIE Transactions*, Vol. 11, No. 1, March 1979.

[23] Chase, R. and Aquilano, N., op. cit., pp. 395-441, 541-569.

[24] Narasimhan, S., McLeavey, D., Billington, P., op. cit., pp. 585-613.

[25] Alkaner, S., and Ölçer, I.A., "Ship Production Scenario Analysis Using Multiple Operations Research Techniques," *Transactions, 8th International Conference on Computer Applications in Shipbuilding*, Sept. 1994, pp. 8.85-8.97.

[26] Amemiya, T., "Production Planning System for Oppama Shipyard," *8th International Conference on Computer Applications in Shipbuilding*, Sept. 1994, pp. 12.3-12.14.

[27] Kuhlmann, T., Marciniak, Z., and Maßow, C., "Integrated Coordination Modules for the Shipbuilding Industry," *Transactions, 8th International Conference on Computer Applications in Shipbuilding*, Sept. 1994, pp. 12.39-12.53.

[28] Tzannatos, E., and Markakis, K., "Computer-Aided Planning of Shipbuilding Operations," *Transactions, 8th International Conference on Computer Applications in Shipbuilding*, Sept. 1994, pp. 12.67-12.77.

[29] Filipic, B., and Srdoc, A., "Task Scheduling and Resource Management in Ship Repair Using a Genetic Algorithm," *Transactions, 8th International Conference on Computer Applications in Shipbuilding*, Sept. 1994, pp. 15.17-15.28.

[30] Gribskov, J., "A Group Technology Approach to Master Scheduling of Shipbuilding Projects," *Journal of Ship Production*, Vol. 5, No. 4, Nov. 1989, pp. 249-255.

[31] Neumann, R.J., and McQuaide, D.J., "Application of PC-Based Project Management in an Integrated Planning Process," *Journal of Ship Production*, Vol. 8, No. 4, Nov. 1992, pp. 191-204.

[32] Neumann, R.J., "Network Scheduling Development in an MRP II Environment," *Journal of Ship Production*, Vol. 10, No. 4, Nov. 1994, pp. 223-232.

[33] Correll, J.G., and Edson, N.W., Gaining Control: Capacity Management and Scheduling, Oliver Wright Ltd. Publications Inc., Essex Junction, VT, 1990, pp. 60-63.

[34] Chase, R. and Aquilano, N., op. cit., pp. 694-750.

[35] Narasimhan, S., McLeavey, D., Billington, P., op. cit., pp. 350-394.

[36] Neumann, R.J., op. cit.

[37] Scott., B., Manufacturing Planning Systems, McGraw-Hill, New York, 1990, pp. 127-148.

[38] Chase, R. and Aquilano, N., op. cit., pp. 906-930.

[39] Narasimhan, S., McLeavey, D., Billington, P., op. cit., pp. 561-584.

[40] Goldratt, E., The Haystack Syndrome - Sifting Information Out of the Data Ocean, North River Press, Inc., Croton-on-Hudson, NY, 1990, pp. 163-262.

[41] Rack, F.H., "Significantly Reduced Shipbuilding Costs Through Constraint(s) Management," *The National Shipbuilding Research Program 1989 Ship Production Symposium. Proceedings.*, Sept. 1989, pp. 17-1 - 17-17.

[42] Chase, R. and Aquilano, N., op. cit., pp. 787-817.

[43] Narasimhan, S., McLeavey, D., Billington, P., op. cit., pp. 508-512.

[44] Suresh, J., "A Simulation-Based Scheduling and Management Information System for a Machine Shop," Interfaces, Vol. 6, No. 1, November 1975.

[45] Amemiya, T., "Process Planning System of CIM for Shipbuilding," *Computer Applications in the Automation of Shipyard Operation and Ship Design, VII*, 1992, pp. 139-150.

[46] Bozenhardt, H.F., "Managing Complexity: AI in Batch Plant Scheduling," Handbook of Expert Systems in Manufacturing, McGraw-Hill, New York, 1991, pp. 152-161.

[47] Chorafas, D., Expert Systems In Manufacturing, Van Nostrand Reinhold, New York, 1992, pp. 199-212.

[48] Maus, R. and Keyes, J., Handbook of Expert Systems in Manufacturing, McGraw-Hill, New York, 1991, pp. 152-161.

[49] Butler, J., and Ohtsubo, H., "A Distributed Problem Solving Based Model for Shipyard Scheduling," *Transactions, Computer Applications in the Automation of Shipyard Operation and Ship Design, VII*, 1992, pp. 313-322.

[50] Parunak, V., Baker, A., and Clark, S., "The AARIA Agent Architecture: An Example of Requirements-Driven Agent-Based System Design," http://www.iti.org/, July 1996.

[51] Shine, J., "Herd Mentality," *Wired*, Vol. 4, No. 6, June 1996, pp. 98-104.

[52] Alfeld, L., *The Virtual Shipyard - Simulating the Ship Construction Process*, NAVSEA and Advanced Marine Enterprises, September 1992.

[53] Spicknall, M., *UMTRI Marine Systems Division Final Report: Evolution of Shipbuilding Simulation Tools Using Realistic Shipyard and Product Contraints*, NSWC-CD and Westinghouse Machinery Technology Division, January 1995.

Some Other Relevant Information Resources

Shipbuilding-Specific Resources

Chirillo, L.D., *Flexible Production Scheduling System*, National Shipbuilding Research Program, NSRP 0238, April 1986.

DeVries, R.L., "Computer-Aided Process Planning: A Path to Just-in-Time Manufacturing for Shipyards," *Journal of Ship Production*, Vol. 4, No. 3, Aug. 1988, pp. 197-215.

DeVries, R.L., Allen, M.A., Jasper, M.L., and Barley, F.J., *Computer Aided Process Planning for Shipyards*, National Shipbuilding Research Program, NSRP 0266, August 1986.

Koga, K., Ito, K., Nakai, Y., and Fujita, J., "Intelligent Design System of CIM for Shipbuilding," *Transactions, Computer Applications in the Automation of Shipyard Operation and Ship Design, VII*, 1992, pp. 323-333.

Lazarus, P., "Reorganizing the Manufacturing Plant," *Professional Boatbuilder*, No. 29, June/July 1994, pp. 22-33.

Minemura, T., "Scheduling Model of CIM for Shipbuilding," *Transactions, 8th International Conference on Computer Applications in Shipbuilding*, Sept. 1994, pp. 12.25-12.37.

Nakamura, M., Horiuchi, K., and Minemura, T., "Scheduling System of CIM for Shipbuilding Applied Product Model, Process-Equipment Model and Operation-Resource Model," *Transactions, Computer Applications in the Automation of Shipyard Operation and Ship Design, VII*, 1992, pp. 151-163.

Park, K.; Lee, K.; Park, S.; Kim, S., "Modeling and Solving the Spatial Block Scheduling Problem in a Shipbuilding Company," *Computers and Industrial Engineering*, Vol. 30, No. 3, July 1996, pp. 357-364.

Powell, P.C., and Zigelman, C.I., "Formal Manufacturing Approaches to Modern Shipbuilding," *Journal of Ship Production*, Vol. 5, No. 3, Aug. 1989, pp. 188-199.

Spicknall, M.H., "Developing and Using an Expert System for Planning the Production of Structural Piece-Parts," *Journal of Ship Production*, Vol. 8, No. 3, Aug. 1992, pp. 163-183.

Storch, R.L., and Chirillo, L.D., "The Effective Use of CAD in Shipyards," *The National Shipbuilding Research Program 1992 Ship Production Symposium. Proceedings.*, Sept. 1992, pp. 2B2-1 - 2B2-10.

Storch, R.L., and Hills, W. "Computer-Aided Manufacturing in Small Shipyards: A U.S. and U.K. Comparative Study," *Journal of Ship Production*, Vol. 11, No. 2, May 1995, pp. 81-89.

Non-Shipbuilding Resources

White Papers From the *American Production and Inventory Control Society, APICS* (http://lionhrtpub.com/apics/)

Baker, T. and Cleaves, G., "World-Class Performance Through Improved Planning and Scheduling Integration," October 1991.

Gilman, A, "Is MRP For You?," March 1995.

Gilman, A., "Interest in Finite Scheduling is Growing...Why?," August 1994.

Hunter, M., "How To Make A Realistic Production Plan," June 1992.

Kiran, A. and Willingham, T., "Simulation: Help For Your Scheduling Problems," August 1992.

Marche, S., "The Seven Key Elements to Selecting a Successful Production Scheduling System," March 1996.

McKaskill, T., "There is a Place for Expert Systems in Finite Scheduling," August 1994.

Merithew, C., "How Do You Plan In a Mixed Mode Environment?," October 1993.

Nichols, J. and Thompson, M., "Planning for Real World Production," August 1994.

Pritsker, A. and Snyder, K., "Simulation for Planning and Scheduling," August 1994.

Proud, J., "More Than Just Numbers! Master Scheduling Management Issues," March 1995.

Schutt, J., "The Quiet Revolution: Integrated Systems For Operations Planning," November 1993.

Sharma, K. and Wilson, J., "What's Wrong With Finite Capacity Scheduling?," March 1995.

Suri, A., "Master Production Schedule: The Driver of Planning and Control Systems," July 1992.

Taylor, S. and Bolander, S., "The Rise of Finite Capacity Scheduling," July 1996.

Thompson, M., "Computer Simulation Drives Innovation In Scheduling," February 1993.

Thompson, M., "Why Finite Capacity? Things To Consider When Selecting Scheduling Software, June 1992.

Voet, M. and Dewilde, P., "Choosing a Scheduling package: Thirty Systems Evaluated in Worldwide Survey," November 1994.

Wyman, F., "Thinking About Simulation-Based Scheduling? Here's What You Ought To Know," November 1993.

Zweben, M., "Intelligent Agents: Planning and Scheduling in Real Time," March 1995.

White Papers From the *Institute for Operations Research and the Management Sciences, INFORMS* (http://www.informs.org/)

Adenso-Diaz, B. and Laguna, M., "Modeling the Load Leveling Problem in Master Production Scheduling," 1996.

Arosio, M. and Sianesi, A., "A Heuristic Algorithm for Master Production Schedule Generation With Finite Capacity," 1993.

Chu, S., "A Mathematical Programming Approach Toward Optimized Master Production Scheduling," 1995.

Chung, C. and Krajewski, L., "Planning Horizons For Master Production Scheduling," 1984.

Das, S. and Sarin, S., "An Integrated Approach to Solving the Master Aggregate Scheduling Problem," 1994.

Das, S., "Master Scheduling With Incremental Capacity Allocation and Rolling Horizon," 1993.

Giesberts, P., "Master Production Scheduling: A Function-Based Approach," 1991.

Hong, S. and Maleyeff, J., "Production Planning and Master Scheduling With Spreadsheets," 1987.

King, B. and Benton, W., "Alternative Master Production Scheduling Techniques in an Assembly-To-Order Environment," 1987.

Sridhara, V. and Berry, W., "Freezing the Master Production Schedule Under Rolling Planning Horizons," 1987.

Ware, N. and Fogarty, D., "Master Schedule/Master Production Schedule: The Same Or Different?," 1990.

Zhao, X. and Lee, T., "Freezing the Master Production Schedule for Material Requirements Planning Systems," 1993.

Other Documents

Bensoussan, A., Crouhy, M., and Proth, J.M., "Mathematical Theory of Production Planning," *Advanced Series in Management*, Vol. 3, 1983, pp. 2-15.

Eilon, S., "Five Approaches to Aggregated Production Planning," *AIIE Transactions*, Vol., 7, No. 2., June 1975.

Fraser, J., "Finite Scheduling and Manufacturing Synchronization: Tools for Real Plant Productivity" (with software buyer's guide), *IIE Solutions*, Sept. 1995.

Glover, F., Jones, J., Karney, D., Klingman, D., and Mote J., "An Integrated Production, Distribution, and Inventory Planning System," *INTERFACES*, Vol. 9, No. 5, Nov. 1979.

Jain, S.K., "A Simulation-Based Scheduling and Management Information System for a Machine Shop," *INTERFACES*, Vol. 6, No. 1, Pt. 2, Nov. 1975.

Kahaner, D.K., "Computer Applications, Production Engineering China," http://www.atip.or.jp/, June 1995.

Peng, W., *Knowledge-Based Master Production Scheduler for the Computer-Integrated Manufacturing System*, Ph.D. thesis, http://www.uta.edu/ie/peng.html, 1989.

Proud, J.F., Master Scheduling, a Practical Guide to Competitive Manufacturing, Oliver Wight Publications Ltd., John Wiley and Sons, Essex Junction, VT.

Smith, J., "TOC and MRPII, From Theory To Results," http://www.rogo.com/cac/JJSmith.html, May 1994.

Internet Resources
Organizations are identified in parentheses.

Informational URLs-

- http://ainet.com/opt/csus/jit.htm (Optimal Planning Techniques, Inc.)

- http://lionhrtpub.com/apics/BG/bgo.html (American Planning and Inventory Control Society)
- http://lionhrtpub.com/apics/BG/BGPLMES.html (American Planning and Inventory Control Society)
- http://tamcam.tamu.edu/Papers/scheduling.htm (Texas A&M Industrial Engineering Department)
- http://tamcam.tamu.edu/SBSC/index.htm#Target Environment (Texas A&M, Industrial Engineering Department)
- http://www.cen.uiuc.edu/~ie261/ie262/notes/MRP/IE373-MRP.html (University of Illinois, College of Engineering)
- http://www.cs.cmu.edu/~SW_Managemnt/html/mod_2/mod_2_3.html (Carnegie Mellon University, School of Computer Science)
- http://www.ececs.uc.edu/~mnoschan/agents.html (University of Cincinnati, Department of Electrical and Computer Engineering, and Computer Science)
- http://www.gmcs.co.uk/ (GMCS, Great Britain)
- http://www.industry.net/c/orgindex/apics (Industry.Net)
- http://www.pmi.org/ (Project Management Institute)
- http://www.primavera.com/sources/index.html (Primavera, Inc.)
- http://www.rogo.com/cac/JJSmith.html ("Crazy About Constraints" - Information on the Theory of Constraints)
- http://www.uta.edu/ie/index.htm (University of Texas, Arlington, Industrial and Manufacturing Systems Engineering Department)

System and Software Vendor URLs-

- http://merlion.singnet.com.sg:80/~gilcrest/max.htm (Micro-MRP, Inc.)
- http://ra.pyramid.com/solutions/Partner_Directory/html/0755.html (Siemens)
- http://www.agamasoft.com/ (Agama Software, Inc.)
- http://www.aimcom.com/ (AIM Computer Solutions, Inc.)
- http://www.ainet.com/opt/ (Optimal Planning Techniques, Inc.)
- http://www.alliancemfg.com/ (Alliance Manufacturing Software)
- http://www.amsoftware.com/ (American Software)
- http://www.axiscomp.com/ (AXIS Computer Systems, Inc.)
- http://www.baan.com/3_Solutions/Applications/1_Mfg/default.htm (The Baan Company)
- http://www.batchmaster.com:80/mrp.html (Batchmaster Software Corp.)
- http://www.cincom.com/products/manufac.html (CINCOM)
- http://www.dataworks.com/ (DataWorks Corp.)
- http://www.dcdcorp.com/ (DCD Corp.)
- http://www.dg.com/Solutions-Directory/prd00665.html (Data General Corp.)
- http://www.distinction.com/ (Distinction Software, Inc.)
- http://www.exel.co.uk/pagesMain/productEFACSNT.htm (Exel Computer Systems)
- http://www.fs.com:80/products/specsheets/MRP.htm (Fourth Shift Corp.)
- http://www.i2.com/ (i2 Technologies)
- http://www.inmass.com/ (INMASS/MRP Software)
- http://www.jdedwards.com/ (J. D. Edwards, Inc.)

- http://www.manugistics.com/ (Manugistics, Inc.)
- http://www.mapics.com:80/app/3mpsp.html (MAPICS, Inc.)
- http://www.maxam.com/ (Maxam Holdings, Inc.)
- http://www.minerva-is.com (Minerva)
- http://www.monitor-toronto.com/ (Monitor Systems of Toronto)
- http://www.mrp9000.com/ (Intuitive Manufacturing Systems, Inc.)
- http://www.natlbus.com/pcms.htm (National Business Consultants)
- http://web.onramp.ca/ (Onramp Network Services, Inc.)
- http://www.osas.com:80/products/addon/specs/mrp.html (Open Systems Holdings, Inc.)
- http://www.paragonms.com/ (Paragon Management Systems)
- http://www.peoplesoft.com/ (PeopleSoft, Inc.)
- http://www.plmrocktec.com/ (Plymouth Rock Technologies, Inc.)
- http://www.primavera.com/ (Primavera, Inc.)
- http://www.ramco.com/ (RAMCO Systems Corp.)
- http://www.rtexpertsource.com/dbmB.cgi?es+Specialization+Production Planning (RT Expert Source)
- http://www.sap.com/ (SAP)
- http://www.shivasoft.com/ (ShivaSoft, Inc.)
- http://www.sm.com/ (Systems Modeling Corp.)
- http://www.ssax.com/bpcs/mmm-mrp.htm (System Software Associates, Inc.)
- http://www.synquest.com/ (Synquest, Inc.)
- http://www.sysprousa.com/ (Syspro Impact Software, Inc.)
- http://www.telesismfg.com/ (Telesis MFG)
- http://www.thru-put.com/ (ThruPut Technologies)
- http://www.tiac.net/users/sailboat/ (MCS-3 Software)
- http://www.tipsol.com/ (Total Integrated Product Solutions)
- http://www.tiwcorp.com/ (TIW Technology Corp.)
- http://www.txbase.com/manufacturing/ (TXbase)
- http://www.tyecin.com/ (TYECIN Systems, Inc.)
- http://www.uk.mdis.com/products/chess/chess_master_scheduling.html (MDIS)
- http://www.usersol.com/us1002.html (User Solutions, Inc.)

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