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AUTOMATION IN RANGE SCHEDULING

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Summary

The imposing challenge of space for management is to direct the most complex and massive engineering effort ever attempted to attain objectives of the highest national priority. And within the body of new management knowledge and experience produced in these tasks lie methodologies fundamental to the administration of any large project. The purpose of this paper is to present an operations research model for the range scheduling function. These techniques were derived from an analysis of the Eastern Test Range, but they are applicable to many cases of the general large project scheduling problem. The method is illustrated with test cases.

A model is presented that would provide computer assistance to the scheduler. The model processes data in the following way. First, requested start times and slack are used to develop a primary "network" whose nodes are individual subtasks of range tests and whose arcs define "order" relationships among the tasks. A secondary network is then constructed from the first. "States" of the primary graph—sets of tasks containing all task predecessors—form nodes of the secondary graph; each node is connected by an arc to a predecessor state and to successor states. Construction of arcs among the states is governed by resource requirements and the precedence relationships of the first graph. Any route through the second network is a user-feasible, conflict-free schedule. Management objectives, abstracted into measures of effectiveness, may then be used to select the "optimum" schedule. In particular, the most compact schedule—the feasible schedule with highest utilization—is given by the shortest path through the graph and this objective, in conjunction with user feasibility, is proposed as the selection criteria.

The purpose of the range scheduling model is to produce an assignment of starting times to range jobs such that, based on the planned execution times, there exists in the schedule no conflicts over major range facilities. Both weekly scheduling and the real-time rescheduling task require this capability, so that the mechanics of both problems are satisfied with the same model, though variations for special effects may be needed. Although a new technique is proposed, the end product exists today, and management procedures, familiar to users and suited to the role of ETR is the space program, remain unchanged.

A Summary of Requirements

Management objectives for the Eastern Test Range are, first, to support users in the execution of their programs, and within these constraints, to operate in an efficient, economical fashion. The range scheduling function implements management objectives in the range schedule. Therefore, the primary requirement in scheduling is to develop feasible assignments: schedules that conform to user-requested start times, commit to users a set of range instruments, and give the user the opportunity to collect data at the required level of accuracy. If there is more than one feasible schedule, additional criteria may be applied to select a schedule that improves on some measure of effective range operations.

Range scheduling is responsible for an efficient plan of user test performance. The tasks required by this responsibility are varied, but this study has concentrated on two important categories:

1. The compilation of trial schedules
2. The resolution of conflicts over equipments and frequencies

The study objective was to isolate scheduling jobs amenable to automation and to develop models useful in computer processing. For example, a combinatorial approach was defined that not only produces feasible schedules, but provides for the selection of one "optimal" schedule. In addition, the technique presents for resolution only those conflicts that may not be disposed of with rescheduling. Thus, only the minimum amount of conflict resolution need be undertaken.

A trial schedule is an arbitrary assignment of start times to jobs. The assignment usually conforms to user requests, but in case irresolvable conflicts exist, it may contain deviations from user schedules. Experimental changes in requested times require the best judgment of the range scheduler, because, if all conflicts are resolved, the new start times are proposed to the individual users as "good" alternatives. In the event the user does not approve a change in start times the trial solution, however desirable, may have no use at all. The ability to generate likely schedules is highly dependent on the amount and "mix" of the workload. Many jobs, for technological or other reasons, have rigid starting times—to meet a tight launch window or satellite pass. Other tests may be moved about on the schedule with various degrees of slack. Prospective increases in the orbital workload will bring a rise in range tests with fixed starting times.
Therefore, flexibility will be increasingly denied the scheduler at the same time utilization rates are increasing. Under such circumstances it is to be expected that likely trial solutions will be difficult to generate by intuition.

The trial schedule is only a candidate; it remains to make the assignments feasible by resolving conflicts over equipments and frequencies. Each resolution is a compromise with user requests. For example, the substitution of the 1.16 C-BAND RADAR for, say, the 19.18 - Merritt Island MIPR - may limit attainable accuracy in metric data. It follows that the number of resolutions should be kept as small as possible. One way of minimizing resolutions is to use start time slack to attain a minimal conflict trial solution.

The actual resolution of conflicts entails both a detailed knowledge of the particular situation and the ability to develop satisfactory substitutions and alternative execute times. The first case requires extensive experience and the second imagination and resourcefulness. It appears likely that such decision procedures are too sophisticated to include in an initial automation plan for the range scheduling function. There may be well known priorities or substitutions, such as the replacement of an equipment with its designated backup in case of failure, that could be programmed easily enough, but the more subtle choices are left to the range scheduler. The role of automation in conflict resolution, therefore, is to, first, minimize the actual number of conflicts and, secondly, to present the remaining conflicts clearly to the scheduler and to aid in the resolution process with schedule analysis.

To summarize, the following items are required of range scheduling automation:

1. programs must produce user-feasible schedules to order.
2. specifications for schedule feasibility must be based on the scheduler’s interpretation of the situation and inputted into the program.
3. program inputs, at the same time, must be simple enough for use on the real-time problem and varied enough to handle all test programs.
4. if more than one feasible schedule exists, the one selected should maximize operational efficiency (feasibility insures that users agree, already, on their start times).
5. conflicts are to be minimized through the use of flexibility in the user start times.
6. except for certain specified decisions, conflicts will be resolved by the scheduler aided by the automation model.

These requirements are at the heart of the range scheduling function. Other provisions, such as display and dissemination programs and decision models for conflict resolution, depend on the existence of this capability and may be considered on their own right.

Schedule Compaction

The scheduling model is directed, first, to the compilation of a feasible schedule, but there may be many schedules that satisfy the feasibility criteria, especially if user programs have a great deal of flexibility. The possibility of multiple choice yields the opportunity of applying operational criteria to the final selection. The scheduling model contains the following sequence of events:

1. set up a list of schedules whose elements satisfy user start times, are conflict-free, and provide the opportunity for accurate results.
2. assuming that no schedule on this list is preferred above the others, select the one that is most advantageous for range operations.

Efficient and economical operation may be attained in many ways—for example, through management policy, planning, and appointments. But in scheduling, utilization rates for range instruments are direct quantitative measures of efficiency and economy. The scheduling function is essentially an allocation procedure, where the resource to be divided up is test time on range instruments. Time, can be a limitless resource; thus, the scheduling function may be executed by delaying range activity—that is, by using more of the time resource. Consider the cut and try procedure for trial schedule generation currently in use at ETR. After a few unsuccessful tries it may be concluded that a schedule does not exist that satisfies all test conductors and that a selection must be made arbitrarily. In this case, low priority projects either scrub or accept delays outside their original planning horizons. That is, the workload is stretched out. As long as no tasks are permanently lost and all work carried out by, say, the end of the current week of operation, the long-term utilization rates are not affected. However, with new satellite programs, manned orbital support and increasingly complex launch problems, the following conditions could occur:

1. many range tests may be completely scrubbed.
2. delays in range programs may begin to effect planning schedules. That is, scheduling flexibility will be reduced in following weeks.
3. whole programs may be assigned elsewhere.

Under high workload conditions, therefore, range schedules must minimize the allocation of time beyond user request intervals. This objective is accomplished if the maximization of utilization rates is an objective of scheduling.
The utilization criterion is used by the proposed scheduling model to select a best operational schedule from the list of user feasible schedules. Now, a measure of effectiveness must be derived. Suppose a quantity of work has been requested for a day of the week. The problem is to schedule as much of this quantity as possible. Consider the following two definitions:

\[ I = \text{an interval of time in the day of length } t. \]
\[ Q(I) = \text{the maximum quantity of work that may be scheduled in } I. \]

Thus, the \( Q(I) \) schedule yields the highest utilization rates of any other schedule in \( I \), considering, of course, that some work must be eliminated because of irresolvable conflicts. In the event of conflicts, induced by user requests, the combination that contains the greatest workload is chosen for \( Q(I) \). It is assumed that all projects making up the quantity of work are equally desirable. Consider, now, that the length of \( I \) is increased. Then, \( Q(I) \) increases until, for some length all tests have either been started or have been delayed beyond the given slack interval. The quantity \( Q(I) \) can not now be improved by lengthening the time interval, and, in fact, \( Q(I) \) is the largest quantity of the total workload that may be scheduled in the requested day. Therefore, if the maximal workload \( Q(I) \) is scheduled in the shortest interval \( I \), the utilization rates are maximized, for increases in \( I \) without corresponding increases \( Q(I) \) will reduce the rate of instrument usage.

Note that the workload \( Q(I) \) assumes that all projects are equally desirable—that is, have the same priority. If this assumption is not strictly true, the total workload, \( Q \), can be broken into priority classes, say \( Q(1), Q(2), \ldots, Q(n) \), and the procedure carried out within each homogeneous priority class. Then \( Q(I) \) would be a maximum workload for interval \( I \) of the following kind:

1. maximum quantity of \( Q(1) \) in \( I \)
2. maximum \( Q(2) \) given \( Q(1) \) in \( I \)
   
   
   
   
s. maximum \( Q(s) \) given \( Q(1), Q(2), \ldots, Q(s-1) \) in \( I \), etc.

Thus, \( Q(I) \) contains the maximum portion of \( Q(s) \) that can be scheduled after satisfying the higher priority requests.

The discussion may be summarized in the following scheduling objective. Suppose out of some quantity of work, \( Q \) is the maximum amount that can be scheduled, regardless of time restrictions. Then \( Q \) should be scheduled into the shortest interval possible. That is, the workload \( Q \) should be compacted into an interval \( I \).

### Operational Environment

The purpose of the Eastern Test Range in the National Space program is to provide support to range users in the most economic fashion consistent with user-imposed constraints. Support involves prelaunch system checkout, range safety services, and the collection and processing of metric and telemetry data. The range user constrains the operation by specifying range equipment, frequencies, task start times (or intervals) and priorities for job execution. This commitment to user needs is stated most directly in the ETR range operations contract with Pan American Airways wherein incentive fees are awarded for the prompt execution of tests and penalties are assessed for holds, delays, and scrubs.

There are many types of range resources that may be allocated to launch and orbital test programs, including manned tracking, telemetry, and control sites; transportation and communication facilities; display devices; housing, test instrumentation and support equipment; and manpower for management, operations, maintenance, and planning. The Eastern Test Range operates major permanent sites at Patrick AFB, Cape Kennedy, Merritt Island, Grand Bahama Island, San Salvador, Grand Turk, Antigua, Puerto Rico, Trinidad, Ascension, and Pretoria, South Africa. In addition sites are maintained at other mainland and off-shore locations and on aircraft and ships. At each site there may be several instruments. To schedule even a project of modest proportions hundreds of men and equipment items must be selected and allocated.

It is the function of range scheduling to bring order to range operations by allocating conflict-free test time to range users. These allocations are made on a weekly and real-time basis, although the entire scheduling cycle is a detailed, lengthy process.

The range scheduling function may only be executed by a centralized unit if the total commitment to a test program depends in fact on the availability of a relatively small number of critical resources. The composition of such a list has been discussed previously in studies of the ETR scheduling process; the elements of this critical set are the major resource items naturally considered first by range scheduling officers in the allocation procedure. Table 1 itemizes categories of critical subsystems. Although this list does not contain all limited facilities, none of the few omissions are likely to cause problems in support and operations.

- C-Band Pulse Radar
- UHF Pulse Radar
- C-W Radar
- Telemetry
- Command/Control & Supervisory Control
Workload items impose a variety of operational problems on the Eastern Test Range. Range activity may be classified in five mission areas: major launch, manned orbital support, satellite support, foreign technology, and instrumentation support.

Major Launch. Missile launches require both data collection and range safety. Systems, particularly in the Cape Kennedy area, may have dual assignments. Most range instrumentation, throughout the count-down and flight time, will be committed in this type of operation.

Manned Orbital Support. Manned orbiting vehicles at present are supported with a limited number of data collection systems during the sequence of orbits that pass over the Eastern Test Range. Since ETR is extensive, the manned orbital support assignment will be significant. There is no expectation that major high-priority operations will suffer lengthy delays in obtaining range support.

Satellite Support. Satellites systems support is similar to the manned orbital problem except that the unit of assignment is one orbit rather than a sequence of orbits. On a read-out pass command/control sends an order to read-out satellite health, rewind the tape recorder and transmit. Data obtained on previous orbits and stored on tape are transmitted to the ground receiver. All communications from the satellite to the ground is via telemetry link, including metric data, for ephemeris computation, is obtained from the telemetry read-out.

Foreign Technology. A significant task at ETR is the monitoring of dark satellites and such tracking may carry the very highest priority. When a particularly important object is encountered, support may be heavy for 8-10 days from initial detection.

Instrumentation Support. This class consists of all jobs involving instrumentation problems—such as pre-launch RF checks on missiles, maintenance tasks on range instruments, and systems R&D. The commitment may be very simple—when, say, a C-Band Radar is used in research—or very complex. In fact, each launch is pretested many times with the full t minus zero range instrumentation configuration.

A survey of the five missions indicates that ETR has many operational modes. On missile launches the entire range must "come-up" and stay at readiness for several hours. On the other hand, individual sites, such as Antigua and Ascension, operate independently on orbital support, using radar, Command/Control, and telemetry. Foreign Technology requires range coordination between tracking sites, mainland Data Processing sites, and communication links, without the full involvement of a launch. Maintenance problems may require only individual instruments.

Range safety and data collection instruments are complex, sensitive devices. The preparation time for any one facility is a significant portion of the total operational time. For example, from a "cold" state the Azusa C-W system requires 300 minutes of set up and pre-calibration time and 45-60 minutes of post-calibration to obtain full design accuracy. This "turn-around" requirement cannot always be stated so precisely, for the test-to-test time is not only a function of equipment assigned to in the previous test, but also of subjective judgments concerning required accuracy. A model, or mental picture, of turn-around or test-to-test is included in any scheduling process, whether manual or automated. Modifications of the "ideal" or "desired" times are made by the scheduler during the bargaining process when compromises in accuracy are made in favor of operational efficiency. The objective of range management, however, is to allocate sufficient time so that the user has the opportunity to collect data at his required level of accuracy.

The Scheduling Cycle

Planning. Range support to missile launch and orbital problems is the subject of intense negotiation between the Test Conductor and the ETR planning group. The outcome of these meetings is an operational directive that sets forth instrumentation and frequencies the range will provide the user and the sequence of events that will occur (the countdown). Deviations from the OD are allowed and final operations are planned after the users TWX changes have come down, although no substantial changes in instrumentation are expected.

Weekly Scheduling. During the week before his test time, the user submits his support request to the range scheduling officers. He specifies (1) a test number and an OD number, (2) required changes, and (3) the day and time of test. This request must compete with all other jobs for time on the range. If there are no other test requests that conflict or if his priority is sufficiently high, the test will be scheduled at the time specified. On the other hand conflicts over range facilities and low priority will result in a change of start time.

The scheduling officers receive the test requests and compose a weekly schedule. This is an iterative process. The initial assignment is formed from requested times and the result is analyzed for conflicts. Resolution
may be affected by changing the start times of jobs with lower priorities, but under severely restrictive conditions it may be necessary to propose substitutions of instruments or even delete some facilities or frequencies. Such changes—in start time and support—may be made independently of the range user; however, the scheduler is usually aware of the special problems of each conductor. As changes are made, new conflicts may be created and resolved. A final version is eventually developed and published on the Thursday immediately preceding the week scheduled. At this point dissatisfied users may bargain further with the range for additional support or test time or go to higher authority and try to override the official schedule. Because ETR exists to service range users, the scheduling office will try to work out a compromise with the Test Conductor.

At some point a weekly schedule will have been established. The user may then prepare his own schedules for operational crews, test equipment, systems checkout and the like. He will recognize, however, that his time assignment on the weekly schedule may not be firm; rather real-time changes from holds and scrubs force revision after revision on the range operations.

Real-Time Scheduling. The most critical scheduling processes occur in or near real-time. There are, in fact, two problems. One is the compilation, production and distribution of a current four-hour schedule. The second is the momentary rescheduling decision that must be made upon the occurrence of a contingency.

The four-hour schedule at the time of issue is conflict-free. Not only are recent real-time changes summarized at this time, but also new conflicts introduced by these changes are resolved. Thus, the weekly planning schedule is made operational, at least formally, in four-hour segments and range users must be alert to possible new assignments.

When a contingency occurs and a project goes into a hold of some estimated length, the scheduler is faced with several problems. How can the schedule be rearranged so that the rest of the day's operations can be executed? If certain tests are scrubbed, can they be rescheduled at requested times? The ability of the scheduler to resolve his real-time problems determines for a large part the operational efficiency of the Eastern Test Range.

Operations Analysis

The range scheduling model is based on a network approach to large combinational problems. Network nodes are sets of subtasks of projects and arcs indicate possible predecessor and successor job sets. Clearly, in order to mold the scheduling problem into a network format it is necessary to interpret the continuous flow of work and time as occurring in discrete chunks. In addition, order relationships between jobs must be exactly specified. The following assumptions, based on an operations analysis of the Eastern Test Range, have been made:

1. Allocations need only deal with discrete time units. This assumption means that there is a minimal time span for tasks on range equipment. Range schedulers have stated that 15 minutes is the smallest interval of time that a facility would be allocated to a range test, and, in fact, 30 minutes may not be too long for most real-time jobs. The weekly planning schedule may allow even grosser allocations, for these assignments are subject to change. Since the actual execution time may vary greatly from the actual planning times, precise specifications in the weekly schedule would be unrealistic and the resulting schedule would be difficult to achieve. The cost of allocating blocks of time is the loss of utilization, but the actual lost time is, in fact, only a small percentage of the total usage of the instrumentation.

The Eastern Test Range is a very large, complex operation. Control is exercised from Cape Kennedy, but operational management is held close to actual sites. Scheduling can implement the required workload by allocating requested facilities, but performance can not be monitored or anticipated. Therefore, for the same reason conflict resolution is restricted to large, critical facilities, schedules may be based on the allocation of time blocks of 15 minutes, 30 minutes, or, possibly, 60 minutes without major effects on range operations. Illustrations used in this discussion are based on a scheduling unit of one hour.

2. A range project may be considered to be a sequence of subtasks, each requiring some set of range facilities. Figure I is a PERT chart of the activity prescribed for the Delta RF Acceptance Operational Directive. There are many separate subtasks. Each day range scheduling must schedule tests of similar complexity. Certainly, it is not possible to schedule the Eastern Test Range at such a level of detail, for the number of combinations of alternative schedules for examination is massive. Even if the possibility existed, it is likely that the resulting schedules would be sensitive to systematic changes in the execution times of the various tests. In addition, detail at the level of Figure I is monitored and controlled by the Test Conductor and instrument operators, who would lose degrees of freedom if these specifications were made in the range schedule. Figure II, below, shows the activity of Figure I as a sequence of subtasks; associated with each subtask is a list of facilities, derived from the basic elements of the individual subtask. For example, subtask A of the illustration is titled "RF tests, Tower on, External Power" and covers all activity through node A of the PERT diagram. Subtask scheduling, rather than individual activities, is simultaneous feasible, flexible, and sufficiently non-restrictive for the range scheduling function.
Figure I - Delta RF Acceptance Operational Directive
Chart by Activity

Figure II - Delta RF Acceptance Operational Directive
Chart by Tasks

Equipment
- Radar: 1.16, 0.18, FPS-8, MOD II, MOD IV, 19.18
  Telemetry: TRI-HELIX Antenna, Receivers (2)
  Command/Control: Low Power Unit

- Radar: 1.16, 0.18, 19.18
  Telemetry: TRI-HELIX Antenna, Receivers (2)
  Command/Control: Low Power Unit

- Radar: 1.16, 0.18, FPS-8, MOD II, MOD IV, 19.18
  Telemetry: TRI-HELIX Antenna, Receivers (2)
  Command/Control: Low Power Unit
3. The individual subtasks of range projects are required to be equal length. This may be done by, first, representing projects as sequences of subtasks and then specifying the task execution time as a multiple of the basic scheduling unit. Each task is duplicated in the final representation by the value of the multiple. The effect of this assumption is the loss of a few percentage points of utilization. If a task of a project is two hours, eight minutes long and the basic scheduling unit is 15 minutes, the task would be represented nine times in the sequence of tasks. Thus seven minutes of facility use would be automatically lost through model design. However, the individual subtasks are, themselves, necessary simplifications of the true activity and the additional disutility is not significant.

4. The individual subtasks of range projects must be executed in continuous sequence. When a user requests test time, he also commits many of his own resources. If an enforced delay occurs, the project will suffer an idle time cost, even though the range may continue to operate economically. Because support is the foremost range criteria, it is assumed that users will only be scheduled for continuous project operation. It is actually possible to schedule a delay in a range test with the proposed scheduling model, but it requires a conscious decision by the scheduler, based on the knowledge of a special situation or concession from range users.

5. Projects may be started at discrete times within the specified interval of slack. If the slack interval is broken up into intervals of length equal to the basic time unit for scheduling, the endpoints of the intervals may be taken to be the alternative start times for the project. This assumption is derived from the fact that it may be advantageous to "do nothing" for a while rather than begin a test at the earliest possible time. Certainly, there is no predetermined pattern of equipment usage over the test length, so that conflicts may be avoided by simply delaying the start time. In this way the demand for the same equipment is solved by "time-phasing" the tests. Since requested equipments will be allocated for the length of the scheduling unit, no advantage may be gained by assuming a finer "net" of alternative starting points than that generated by the basic scheduling unit.

In summary the following assumptions have been made in model construction:
1. Allocations may be based on discrete time units.
2. Individual projects may be considered to be a sequence of tasks, each requiring the same amount of time but possibly different range instrument configurations.
3. The individual tasks of a project must be executed in sequence in consecutive time periods.
4. Projects must begin within a specified slack interval.

**Processing**

The operations analysis of the Eastern Test Range has shown that workload for any period of time may be represented as a network whose nodes are the individual project tasks and whose arcs define their order of execution. This network may also be constructed to include the user requested times. Introduce a dummy project into the workload consisting of one subtask for each scheduling period and no equipment requirements. Now, construct the network in the following way:

1. If a user has no slack and specifies, say, the \( i + 1 \) scheduling period as his start time, connect the first task of his project with a solid line to the \( i \)th node of the dummy job.
2. If a user has a slack interval and if the earliest admissable start time is the \( j + 1 \) scheduling period, connect the first task of his project to the \( i \)th node of the dummy job with a broken line.

For example, let project A have tasks A1 and A2 and project B have tasks B1, B2, and B3. If project A requests a start time of 0400Z with no slack and project B restricts his earliest start time to 0200Z, then the following network is constructed:

```
0100Z 0200Z 0300Z 0400Z 0500Z
A1 -- A2
B1 -- B2 -- B3
```

Any configuration of workload start time and slack may be represented with this format. The first phase of processing in the range scheduling methodology constructs such an activity network.

In the second phase of processing a secondary network is developed from the primary graph. States of the primary graph become nodes of the secondary network, where a state is defined to be a set of tasks that contains the preceding task of every task in the set. That is, a set of subtasks, \( E \), is a state if \( E2 \) in \( E \) and \( E1 \) precedes \( E2 \) implies that \( E1 \) is also in \( E \). For
example, in the configuration displayed above if task B2 is in state E then B1 must also be in E. Therefore, according to this definition, the set of tasks (A1, B1, B2) of the illustration is a state but (A1, B2, B3) is not, for task B1 proceeds B2 and must be in every state B2 is in.

The following rules apply for the construction of the secondary network:

1. For a starting node, write T, consisting of no tasks.
2. Consider all states E. Each E whose tasks may be concurrently scheduled is connected to T with an arc. Each state in the first step must necessarily contain no more than first tasks of range projects.
3. Now consider states in the rth step. Let E be such a state. All projects with some task in E will be called active if its last task is not in E. Now extend each active project of E to the immediate successor. Let the set of immediate successors be called I. If the tasks in I may be scheduled concurrently, then F = E U I is listed in the r + 1 set. The set F is clearly a state for the tasks in I are derived from predecessor tasks already listed in E. Connect F to E with an arc. Now let J be a set of first tasks of project not underway but eligible for starting. If the tasks in I U J may be scheduled concurrently, list state F(J) = E U I U J and connect E and F(J) with an arc. Consider all sets J in this process. If F(J) has already been listed it may be omitted from the r + 1 construction of state E.
4. Continue this construction until S, the state containing all tasks in the workload is reached. Suppose this occurs in step n.

The secondary graph is a network in n + 1 steps, beginning with the zero state and ending with the final state. If state E is connected to state F, moreover, the jobs F - E may be concurrently scheduled. Any path through this network, in fact, will yield:

a. A schedule of tasks for each basic time unit, which is resource-feasible—that is, may be executed without conflict.

b. User feasible—that is, conforms to user requested time, and which

c. Executes all tasks immediately in sequence when the first task has been scheduled.

The only complete schedule corresponds to the path from the zero state to the T state, for all jobs are completed. In addition, because this is the first time T appears, by rule of processing, the path to T also yields the most compact schedule of range workload. (The methodology described in this section was derived in part from a method proposed for the line-balancing problem.)

A Simple Example

The procedure—in particular, the representation and selection process—may be illustrated with a simple example. Although the problem is not difficult, the basic concepts are presented; more representative problems, using a computer program, are included in this report.

Suppose three projects are to be scheduled with the following utilization of equipment:

<table>
<thead>
<tr>
<th>C-Band</th>
<th>0.18</th>
<th>1.16</th>
<th>19.18</th>
<th>Duration (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network readout</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Balloon track</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>FCA checkout</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Let the basic unit of time for scheduling be one hour. Suppose further that the objective is to finish all the work as soon as possible starting at 0800Z and there are no user requested start times. The equipment designated in the table will be assigned for the entire length of the tests. A primary network is constructed from the times.

![Diagram of primary network]

Tasks A1 and A2 correspond to the network readout, B1 and B2 to the balloon track and C1 corresponds to the one hour FCA checkout task. The dotted lines connecting A1, B1 and C1 to 0700 indicate that no mandatory start times have been made.

The secondary network may now be generated from the primary network. Each node, or state, will be "tagged" by its contents. For a starting node write T.
In the first step all sets of first-tasks that are conflict-free are listed; thus, neither \((A_1,C_1)\) nor \((B_1,C_1)\) are entered. For step 2 each entry in step 1 is examined. The required successors of tasks in an entry form a nucleus of tasks for the next period. For example, job \(A_2\) must follow \(A_1\), so that any entry with \(A_1\) must be connected in the next period with an entry containing \(A_2\). In addition to the nucleus tasks all alternative methods of starting new jobs must be considered and feasible arrangements must be listed under the next time period. Step 3 is generated in the same way. If an entry has no feasible successor, the branch of the graph may be terminated.

Among the entries in step 3 is the state \((A_1,A_2,B_1,B_2,C_1)\), the entire set of tasks to be scheduled. The appearance of the final state indicates that a feasible schedule has been obtained and that the most compact schedule terminates in the last hour listed. The route from \(T\) to the final state generates a most compact feasible schedule. Two routes have been found and are marked with hash marks in the above diagram. The two paths yield the following allocations:

**Path 1**

```
0.18  A1 → A2 → C1
1.16  B1 → B2
19.18 B1 → B2 → C1
0700 0800 0900 1000 1100 1200
```

**Path 2**

```
0.18  C1 → A1 → A2
1.16  B1 → B2
19.18 C1 → B1 → B2
0700 0800 0900 1000 1100 1200
```

### A Scheduling Example

The following example demonstrates the use of the scheduling technique on typical missile range problems. Nine range test projects are scheduled on 25 ETR instruments or subsystems. These quantities are not limits for the scheduling model, but were selected to demonstrate the basic operations within a computer program framework and at the same time indicate how some complex situations are processed. The full ETR workload may be efficiently processed with the same technique, scheduling against the entire complement of critical range instruments.

Systems scheduled in these examples represent a sample of critical resources used in many range test programs. A table of subsystems is given below. It shows a variety of instrumentation, and locations. The quantity column gives the number of different tests the instrument may support at one time; most systems are restricted to one job at a time, but this rule is independent of the technique and can be changed if required. The last element on the list is not an instrument at all, but a different kind of resource—C/C frequencies. In the Cape Kennedy area FCA guarantees a +15 mc protective band for operating Command/Control beacons. This frequency model has been included in the computer program.
Table 1 - Critical Subsystems

<table>
<thead>
<tr>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPQ-6 Radar</td>
</tr>
<tr>
<td>Subcable</td>
</tr>
<tr>
<td>CADDAC</td>
</tr>
<tr>
<td>RTC</td>
</tr>
<tr>
<td>Command/Control</td>
</tr>
<tr>
<td>Telemetry</td>
</tr>
<tr>
<td>FPS-16</td>
</tr>
<tr>
<td>Azusa</td>
</tr>
<tr>
<td>Telemetry</td>
</tr>
<tr>
<td>TPQ-18 Radar</td>
</tr>
<tr>
<td>Command/Control</td>
</tr>
<tr>
<td>Telemetry</td>
</tr>
<tr>
<td>TPQ-18 Radar</td>
</tr>
<tr>
<td>Command/Control</td>
</tr>
<tr>
<td>Telemetry</td>
</tr>
<tr>
<td>FPQ-6 Radar</td>
</tr>
<tr>
<td>Command/Control</td>
</tr>
<tr>
<td>Telemetry</td>
</tr>
<tr>
<td>TPQ-18 Radar</td>
</tr>
<tr>
<td>UHF Radar</td>
</tr>
<tr>
<td>Command/Control</td>
</tr>
<tr>
<td>Telemetry</td>
</tr>
<tr>
<td>FPS-16 Radar</td>
</tr>
<tr>
<td>Command/Control</td>
</tr>
<tr>
<td>Telemetry</td>
</tr>
<tr>
<td>Frequencies</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subsystems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Several channels</td>
</tr>
<tr>
<td>1 High power</td>
</tr>
<tr>
<td>4 Low power</td>
</tr>
</tbody>
</table>

Table 2 - Sample Input Specifications

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Test Name</th>
<th>Length</th>
<th>Start Time</th>
<th>Calibration</th>
<th>Priority</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>Manned Orbital</td>
<td>09</td>
<td>10 10 10</td>
<td>00 00</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>400</td>
<td>Satellite Track</td>
<td>04</td>
<td>20 20 20</td>
<td>00 00</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>500</td>
<td>Readout Hawaii</td>
<td>01</td>
<td>12 12 12</td>
<td>00 00</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>Readout 12</td>
<td>11</td>
<td>11 11 11</td>
<td>00 00</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>8065</td>
<td>Delta RFI</td>
<td>07</td>
<td>15 15 17</td>
<td>00 00</td>
<td>2</td>
<td>Delete 0.18</td>
</tr>
<tr>
<td>6045</td>
<td>Gemini Simulation</td>
<td>09</td>
<td>03 04 04</td>
<td>00 00</td>
<td>2</td>
<td>Phase 1</td>
</tr>
<tr>
<td>2025</td>
<td>Balloon Track</td>
<td>03</td>
<td>10 10 12</td>
<td>00 00</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>7055</td>
<td>Arcas Launch</td>
<td>02</td>
<td>11 11 13</td>
<td>00 00</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Input Specification

The input specification, which contains all information required to run the scheduling program, is given in Table 2. The Test Number and Test Name are used to retrieve from a data base such O.D. information as equipment usage, test time, and frequencies. Start time data consists of three inputs: 
- E = earliest allowable start time, R = requested starting time, and L = latest allowable start time. The difference between L and E is called project slack and measures the flexibility the scheduler has in scheduling tests. In the example orbital support work and high-priority range tests are listed without slack indicating that the range is prepared to support the program at the requested time. The range scheduler may use slack according to his interpretation of the importance of test timing. Another interpretive input is the priority number. The range projects may be rated subjectively or according to some official priority scheme, in priority classes or singly, or priority may be ignored entirely. The important point is that the prospect of scheduling a test at the requested time and with the full complement of requested equipment improves as the priority ranking of the test goes up.

Data Base

The program retrieves from a data base time and equipment specifications for test projects on the schedule. A Gantt chart was produced for each test.
from the Operational Directives—time is referenced against either T minus zero or S (start) time. These requirements are coded into a data base with an equipment versus scheduling time unit matrix. The program locates a time for S (or T) and the major events are assumed to occur as given in the Gantt chart. A chart of the Delta RF Test is given in Figure III.

### Program Output

Program output presents in tabular form the derived schedule. Activity on a test in some one of 24 hours is denoted by a non-zero integer, and the (hours within) scheduled time interval is numbered consecutively from one through the total test length. The basic time period for scheduling in these sample problems is one hour—no finer allocations are made.

Priority classes are processed in order of ranking. The highest ranked set is scheduled first and the commitments fixed. The second level class is scheduled against this fixed commitment and the resulting allocation is also made firm. The process is iterated through all priority levels. If, during scheduling, no activity may be assigned to an hour because of equipment or frequency conflicts, the program outputs conflict analysis information. All equipments and/or frequencies causing the problem are detected and printed, together with the requesting projects.
Analysis

The outputted schedule is analyzed in Figure IV. The bar chart depicts scheduled activity on each critical range instrument. The assignment, especially for mainland instrumentation is quite dense, with the Patrick MIPIR allocated 12-1/2 hours of workload—or 52% utilization for the 24 hour period. Several other systems are assigned between eight and ten hours.

Project numbers at the top of Figure IV describe the Patrick MIPIR schedule. At the start of activity the radar supports the Gemini simulation (#6045), continues on to skin track an ARCAS launch (#7055), beacon track a manned orbiting vehicle (#300), and finish on the Delta RF Acceptance tests. On the first program run no deletions were made (see Table 2) and an irresolvable conflict was detected in hour 18. The program stopped processing the schedule to analyze the conflict and printed out the conflicting instrumentation (Patrick MIPIR) and tests (manned orbital support and Delta RFI). A manual resolution was then required before processing could continue. As noted in Table 2, the Patrick C-Band was deleted from the Delta RFI phase 1 requirements (see Figure III). With this change a complete, conflict-free schedule was generated.

Additional Problems

There are two problems that have not been directly attacked, but for which solutions may be outlined. These are:

1. turn-around and calibration scheduling
2. analysis of task groups for conflicts

The turn-around time between tests depends both on the equipment requirements of each project and their modes of operation. For example, if test A uses the
0.18 MIPIR fully calibrated, then test B may use the same Radar later with less pre-calibration. Similarly, the interval between usage of every range instrument will vary with the changes required to attain the operational state. This process has not been introduced into the computer scheduling program procedure. Models to automatically derive turn-around time are not difficult to formulate. For example, notice that in the scheduling technique one list of states is used to generate the possible assignments for the next time periods. A state is tagged by its contents—the tasks that have already been assigned in the scheduling period under consideration. Since knowledge of the operational mode of an instrument may be obtained from a history of its usage, the turn-around times for successors to any one state may be computed and introduced during the construction of the secondary network, applied as a constraint on the successors.

The second problem is the analysis of the task groups for conflicts. The method used in the computer code is to allocate an equipment entirely to a project if it is requested during some basic scheduling unit. For example, consider the table:

<table>
<thead>
<tr>
<th>Equipment</th>
<th>0.18</th>
<th>1.16</th>
<th>19.18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task A</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Task B</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

If Task A requests the 1.16 and 19.18 C-Band Radars and Task B requests the 0.18 and the 19.18, the following Boolean operation is performed:

\[(0,1,1) \times (1,0,1) = (0,0,1)\]

If the result of this multiplication contains all zeros, no conflicts exist in the tasks. For the example the conflict over the 19.18 Radar is immediately detected.

If neither Task A nor Task B require the full time usage of the requested equipments, the usage rates serve as comparison parameters.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>0.18</th>
<th>1.16</th>
<th>19.18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task A</td>
<td>0%</td>
<td>100%</td>
<td>37.5%</td>
</tr>
<tr>
<td>Task B</td>
<td>75%</td>
<td>0%</td>
<td>37.5%</td>
</tr>
</tbody>
</table>

Instead of a Boolean operation a comparison would be made on, say, the maximum usage rate. For example, if two tests are to be scheduled on an instrument, the maximum utilization may be set at 75%, allowing for change-over. Then, the following operation is performed:

\[(0,100,37.5) \times (75,0,37.5) = (75,100,75)\]

The utilization rate for the 19.18 is 75% and, therefore, no conflict is detected. The problem may also be solved by reducing the size of the basic scheduling unit such that at most one task could be processed on any instrument.

References
