INTRODUCTION

Some Recent Developments

Work planning, a never-ending management responsibility, has been aided tremendously in recent years by the development of a new technique commonly referred to as networking or arrow-diagramming. Today, the network is widely accepted by business, scientific, and governmental organizations as a worthy replacement for the Gantt chart and other less flexible and less meaningful methods of planning work.¹-³, ⁹, ¹²

PERT,⁴ Critical Path Method (CPM),⁵, ⁶ and many other similar systems⁶ use estimates of the time required to complete each activity as the basis for determining the work schedule. The scheduling system sequences all the activities in the network and calculates the earliest and latest completion dates for each activity. These dates are then woven together to form a schedule for the total project. In some instances the scheduling function is automated, that is, an electronic computer is used to perform the calculations; in others the schedule is determined manually and monitored with the aid of a computer.⁹

RAMPS, a system for Resource Allocation and Multi-Project Scheduling, was recently developed by C-E-I-R, INC. and now is an operational IBM 7090 digital computer program. RAMPS retains many of the basic concepts of its predecessors; it uses the network for work planning and relies on a careful analysis of the needs of each individual activity, but it also has unique features not found in other systems. Two of these are readily apparent in its name—Resource Allocation and Multi-Project Scheduling.

Activity Resource Requirements

Major differences among many networking systems lie in the information provided for each activity and ultimately used in the work scheduling function. In most systems, this information includes estimates of the time needed to complete each activity and the total cost of the activity or a related group of activities. Where a schedule is produced, it attempts to reflect the most desirable time-cost relationships.

While RAMPS includes time and cost considerations in its work schedules, it also incorporates the resource requirements of each activity and the availability of these resources at the time the activity is to be scheduled—both extremely vital factors in any meaningful scheduling system.

Multi-Project Schedules

A unique feature of RAMPS is its ability to schedule simultaneously more than one work
project. The projects to be scheduled may differ in size, type of work, importance and starting times. They are related only in their reliance on a common pool of resources.

RAMPS recognizes and responds to established priorities for the projects and competition among activities within all projects for limited quantities of available resources. The system also strives to meet established target completion dates by applying larger quantities of available resources to critical activities within all projects.

**Competition for Available Resources**

In addition to defining the work and resources required by the various activities, the RAMPS user provides the system with a knowledge of the quantity of each resource type that is available to all projects. Provision is also made for using overtime or additional units of a given resource at a premium cost.

There may be many activities in all projects competing for the same resources during the same work period. RAMPS weighs the needs of each activity individually and in relation to the other activities before deciding how the resources are to be allocated.

**Management Controls**

Under the many constraints imposed by completion deadlines, specified resource limits and project priorities, RAMPS must weigh many factors before deciding how best to schedule each project. Frequently, there are many possible routes that RAMPS could follow, each with a different effect on the schedules produced. There is, for example, the route that minimizes project completion time, but perhaps at an increased cost because of the use of overtime. Another route may assure a minimum of idle resources throughout the lives of the projects, and another might maximize the total number of activities being worked on during each scheduled work period. In instances such as these, RAMPS relies on control information provided by the RAMPS user to determine which course of action is most desirable. This ability on the part of management to influence and guide the scheduling function is one of the major features of the RAMPS system.

**ESTABLISHING THE NETWORKS**

**General Description**

The foundation of the RAMPS system is the network—a graphic display of a plan. The network portrays an orderly step-by-step series of actions which must be performed successfully in order to reach a specific, definable objective. Simply stated, a network is a work flow diagram.

**Concurrency in the Network**

In almost every real situation, there are many activities that can be carried on concurrently; others must be accomplished in a purely serial fashion. By planning to allow several related efforts to proceed simultaneously and converge at the proper event, the manager is able to reach his stated objective in a much shorter period of time. Since the network is a work plan, those activities which logically can be worked on in parallel should be shown in the network as concurrent activities. The concept of serial and concurrent activities is shown in Figure 1.

![Serial and Concurrent Work Flow Diagram](From the collection of the Computer History Museum (www.computerhistory.org))
It is obvious that a considerable amount of effort must be expended to determine which activities may be concurrent and which must proceed alone. But it is this effort at the planning level that saves time and money later when the actual work is done.

ESTIMATING TIME AND RESOURCE REQUIREMENTS

General Description

Although the importance of an accurate and well-planned network cannot be over-emphasized, there is perhaps no other function in the total application of RAMPS that is more important than obtaining accurate estimates of the time and resources required by each activity. Because RAMPS bases many of its scheduling and resource allocation decisions on this information, the validity of the schedules produced hinges on the thoroughness with which time and resource requirements are estimated. It is imperative that these estimates be made by those individuals who are most familiar with the work to be accomplished by each activity.

Determining Amount-of-Work

With the preliminary networks drawn and available as work guides, the next step in applying RAMPS can begin: determining the amount-of-work required by each activity in the networks.

Amount-of-work is derived from multiplying the number of unit time periods required to complete an activity under normal working conditions by the number of units of resource required per time period. The unit time period may be an hour, day, month, or any unit of time that defines the smallest period within which work will be scheduled and resources allocated.

Although it is not necessary to record amount-of-work in the network, it is frequently beneficial because it provides a ready visual display of the time and resource estimates for each activity as illustrated in Figure 2. The amount-of-work figures are enclosed in boxes below the activity lines. The units of resource required per time period are recorded beside the amount-of-work boxes. The estimated number of time periods needed to complete each activity can be quickly determined by dividing the units of resource figure into the amount-of-work.

If we assume that under normal conditions activity 3-6 of Project A will require three days to be completed and will consume the work of two painters during each day, the amount of work for the activity would be six units. The amount-of-work concept provides the system with unique flexibility in work scheduling and resource allocation. By including two additional resource utilization rates to the normal rate already established, this flexibility can be further increased.

Establishing Alternate Utilization Rates

Under normal conditions, activity 3-6 would require three time periods to be completed and would use two painters per time period. To provide for the possibility of doing the job faster or slower than normal, one can provide two other estimates. The first is a resource utilization rate under accelerated work conditions, speed-up; the second is a resource utilization rate under relaxed or extended work conditions, slow-down. The work efficiency at other than the normal rate is introduced to account for the absence of precise linear relationships.
Once the amount-of-work has been determined for an activity, it should be the guiding factor in determining desirable speed-up and slow-down utilization rates. It is necessary to "tailor" utilization rates and work efficiencies for a given resource to the individual activity to which the resource is to be applied. Each activity in the network and the resources it needs are considered as autonomous units for purposes of estimating amount-of-work, resource utilization rates, and work efficiency at the three utilization rates.

Scheduling and Allocating Flexibility

The three rates of resource utilization provide RAMPS with great flexibility in manipulating time and resources requirements of each activity to meet resource availability levels. The same flexibility extends from the activity level to the project level where the speed-up, normal, and slow-down rates allow the system to adjust work accomplishment rates to meet project completion deadlines.

As shown in Figure 3, Project A could be completed in as few as 9 time periods at the speed-up rate, or as many as 32 time periods at the slow-down rate. At the normal rate, the project could be completed in 16 time periods. Note that the use of each rate requires a different peak work force. The total work force required reaches peaks of 20 men during period 5 at speed-up, 10 men during period 8 at normal, and 6 men during period 15 at slow-down rates.

If all the needed resources were available, it is likely that RAMPS would schedule a project at the speed-up rate. However, in real situations, all the needed resources are rarely available at all times, especially when there are several projects involved.

Let us assume, therefore, that only 7 men are available for work on Project A. Under this restriction, we can examine the steps taken by RAMPS in developing a schedule for that project considered in isolation. We will also see how the three utilization rates are intermixed in the schedule produced.

Determining the Critical Path

One of the first uses of RAMPS makes of the amount-of-work values is in determining the critical path within each project. The critical path is the longest path or sequence of activities, in terms of total time required, from the starting to the ending activity.

All activities on the critical path are critical activities. As shown in Figure 2, there are three possible work paths in Project A, the longest of which requires 16 time periods at normal rates and travels through events 1, 2, 4, 5, 6, and 7. This path is the critical path; any delay in the completion of a critical activity will cause an equal delay in completion of the project. If any or all of the activities not on the critical path are completed ahead of schedule, there could be no time gained in project completion. On the other hand, time gained along the critical path means time gained in project completion. Thus, the critical path calculation provides the following information:

1. The duration of the project if all activities on the critical path are scheduled at the normal resource utilization rate, and
2. The identity of those activities which are critical and therefore must receive preference when they are competing for a limited resource with activities that are not on the critical path.
Therefore, the next step in developing a schedule is determining when there will be competition between critical and non-critical activities for the 7 men that are available. This is done by establishing the earliest possible start times for the non-critical activities so that the total resource requirements for all activities in each time period can be determined. Figure 3 shows the earliest periods at which work on each activity in the project can begin. Note that beginning in period 4, the resources required at normal rates exceed the quantity available.

It can be seen that by using the slow-down utilization rates during periods 4 through 9, a schedule could be produced that stays within the limits of the available resources. However, this can be done only at the expense of extending the project completion time.

Since RAMPS strives to complete each project as quickly as possible, the use of slow-down rates on critical activities is essentially a last resort. Therefore, another alternative must be considered: delaying the start of the non-critical activities so that the resources they would otherwise consume can be diverted to the critical activities. This is called "floating" an activity.

Determining Activity Float

Activity float is the difference in time periods between the earliest time an activity can be completed and the time it must be completed without extending the project completion time. An activity float analysis for Project A is shown in Figure 4. Note that the critical activities have zero float—they cannot be delayed without delaying project completion.

The float for activity 2-6 is five time periods. The earliest time it can be completed is period 9; it must be completed during period 14 to preclude a delay in the start of activity 6-7. This kind of float is called free float because the activity can be delayed without interfering in any way with the float of other activities.

Conversely, activity 2-3 has two periods of interfering float. Since it must be completed before activity 3-6 can begin, 2-3 can be delayed one or two time periods, but only with an equal reduction in the float of activity 3-6. For this reason, the float of activity 2-3 is said to interfere with the float of an activity that is to be started later.

Producing a Schedule

With the combined power of the float analysis and the three rates of resource utilization, RAMPS is now equipped to produce an efficient schedule that meets the work requirements of each activity, minimizes project completion time, and stays within the limits of available resources. An idea of how this power is used can be gained from Figure 5 which shows the schedule produced for Project A.

By delaying the start of activity 2-6 and using the speed-up and slow-down rates where necessary, RAMPS has scheduled the project for completion in 15 time periods using a total work force of only 7 men. Note, too, that idle resources have been minimized where possible.

Although this small example serves to illustrate how RAMPS schedules work, a better idea of the scheduling power of RAMPS can be gained when one considers that this example takes into account only one project and only
one resource type: men. Looking again at the network for Project A, one sees that although men are required in each activity, they have different skills. There are carpenters, painters, electricians, and other skills involved. Therefore, in scheduling this project, RAMPS would not only have to consider total work force, but also the availability levels of each of the skills in each time period.

RESOURCE TEAMING

In our discussions to this point, we have included only the contingency of an activity requiring one resource type. There is a need, of course, for a means of applying several different resources to the same activity while still maintaining the amount-of-work concept. In the RAMPS system, this need is fulfilled by resource teaming.

When an activity requires several different resource types, they are combined to form a resource team for the activity. Each resource team is composed of a lead resource and one or more trailing resources.

The lead resource can be considered the resource in the team upon which the greatest overall demand is levied. It then is used to determine the amount-of-work for the activity and the slow-down and speed-up completion rates. The trailing resources are those “subordinate” resources that are needed to support the work to be done by the lead resource. Although trailing resources may actually perform work on the activity, they do not enter into the amount-of-work calculation. Amount-of-work for resource teams is derived solely from the lead resource date but all resources must be available before the activity can be scheduled.

DETERMINING RESOURCES AVAILABLE

Having covered the first two steps in the application of RAMPS:

1. Project planning and network preparation, and
2. Amount-of-work estimates and resource requirements for each activity in each project,

one must form the resource pools from which RAMPS will allocate the needed resources to the various activities and projects. The task is to determine:

1. How much of each resource type is available,
2. When and how long this quantity is available, and
3. The resource cost.

For each resource, these questions must be answered from two points of view. First, we must determine the answers under normal working conditions or at normal cost. Then we must establish the various means by which additional resource units could be provided if needed. The possibilities include overtime, sub-contracting, and hiring or acquiring additional units.

These additional units are called premium resources and, as the name implies, their unit costs are usually higher than those of the normal resources.

Obviously, normal availability data is required by the RAMPS system; if work is to be scheduled, resources must be provided. Premium availability data is not required, but it is important in providing RAMAPS with further flexibility in accomplishing the required work. Certainly the application of additional resources, derived by any means, will contribute to the completion of the required work in a shorter period of time, but at an additional cost. This data is particularly important when management is willing to incur greater expense to complete a project in a minimum amount of time. The quantity of any resource may be constant over the total scheduling period or may vary in level as a function of time.

Additional resource information needed includes the unit cost per time period, the availability of additional premium resources, and the cost of premium resources.

Although RAMAPS strives to avoid allocating premium resources, it may use them under either of the following two conditions:

1. To meet a project completion deadline when no other means exists for accomplishing the required amount of work within the time specified.
2. To alleviate an otherwise untenable scheduling bottleneck caused by an acute shortage of one or more resources during one or more time periods.

From the collection of the Computer History Museum (www.computerhistory.org)
SETTING MANAGEMENT CONTROLS  
AND OBJECTIVES

General Description

The next, and final, step before operating on the data accumulated so far is the setting of the objectives to be reached in the schedules that are produced. The use of the various controls determines project priority and provides answers to such questions as: “In scheduling all projects, should cost be minimized? Is time important? Should idle resources be minimized?”

Establishing Project Priorities

In perhaps every instance of multi-project scheduling, management can pinpoint those projects which, when completed, will be more beneficial to the company as a whole. Naturally, if these benefits are to be realized as early as possible, these projects must be given priority when all projects are competing simultaneously for a limited quantity of available resources.

Project priority can also be viewed from a slightly different angle: “How much is it going to cost if this project is not completed on time? How much can be saved or gained if it is completed ahead of time?” The answers to these questions are crucial in the many areas of business where work projects are negotiated under bonus-penalty agreements.

The relative importance of the various projects is injected into RAMPS decision-making by providing the system with three facts: project start dates, desired project completion dates, and project delay penalties.

Establishing project starting dates is the first step in exercising control over the schedules produced by RAMPS. This is done merely by specifying the earliest time period at which work may begin on each of the projects to be scheduled.

The desired completion date is expressed in the same manner as the starting dates—the time periods during which the projects are to be completed. In many instances, it is difficult to provide a knowledgeable estimate of how much time, from start to finish, a project should require, particularly when the work is unprecedented. In others, experience will allow reasonably accurate completion dates to be set.

By providing RAMPS with the costs incurred in delaying each project, we can identify those projects with the higher priorities and thus provide the basis for deciding which projects are to be completed on the deadlines indicated if all targets cannot be met.

Control Factors

While the start date, completion date, and delay penalties provide a means for expressing priority among projects, there is also a need for expressing other criteria that are to be observed in the schedules that are produced for all projects. For example, in addition to recognizing the relative importance of projects, management may also recognize a need to minimize project costs, minimize idle resources, or maximize the total number of activities being worked on at all times. These and other needs can be conveyed to RAMPS through the use of the management control factors.

It should be emphasized that RAMPS attempts to complete each project as soon as possible by making the most efficient and appropriate use of time and resources. More specifically, RAMPS continually strives to:

1. Start and complete each activity at the earliest possible time.
2. Achieve a smooth rate of work accomplishment and resource utilization by “looking ahead” for possible bottlenecks.
3. Minimize idle resources.
4. Work simultaneously on as many activities as possible.
5. Give priority to critical activities.
6. Avoid interrupting work on an activity once it has been started.

In forming a schedule of work during a given time period, RAMPS is almost always confronted by conflicts among these objectives; rarely can they all be achieved at the same time. When there is conflict, the program must determine which of these objectives are to be satisfied at the necessary expense of excluding others. For example, consider the following situation: there are four activities that could be started in the current time period and there are adequate resources at the normal utilization rates to start all of them. However, one of the activities is on the critical path and in order to meet the desired project completion time, it must be scheduled at the speed-up rate. This will mean delaying one of the other projects so that the resources it would otherwise consume can be diverted to the critical activity. In addi-
tion, another activity must be completed during the current time period to avert a probable work bottleneck in the subsequent time period. To avoid the bottleneck, a second activity must be delayed so that the activity preceding the possible bottleneck can be accelerated.

Of the four activities that could be started, only two can begin if a work bottleneck is to be averted and a critical activity is to be given priority. The decision to be made is whether the first and fourth objectives are more important than the second and fifth objectives.

Certainly these considerations and decisions are common to any scheduling system. Indeed they are made every day by one means or another. In most instances, however, they come from an individual who is thoroughly familiar with the project being planned and is therefore able to judge the relative importance of each of the considerations.

The control factors that are a part of RAMPS offer a means for expressing the relative importance of the many items that bear on scheduling decisions. Through their use, those who are most familiar with the work to be done and the environment in which it will be done, can provide RAMPS with a means for determining the best course of action when there is a conflict in the overall scheduling objectives.

Thus, the discretionary use of management controls in the situations we have just discussed exercises a direct influence and control over the schedule produced.

**Weighting the Control Factors**

Influence of RAMPS' scheduling decisions is exercised by preparing a table of relative weights for the following six factors:

1. Free Float
2. Total Float
3. Look-Ahead
4. Work Continuity
5. Number of Jobs Scheduled
6. Idle Resources

As shown in Figure 6, each of these factors can be used to exercise a unique influence on the scheduling functions and thus satisfy one of the management objectives mentioned earlier in this section.

The degree to which the schedule is affected by any one factor depends upon its weight relative to the weights assigned to the other factors.

For example, if the paramount consideration in accomplishing the work on a project is keeping idle resources at a minimum, the idle resource factor might be assigned an overwhelmingly high weight in relation to the weights assigned to the other factors. This would indicate to the system that highest emphasis is to be placed on minimizing idle resources in making scheduling decisions.

**Using the Control Factors**

RAMPS first examines the three utilization rates prescribed for each of the competing activities and lists all the possible assignment combinations. The weighted control factors are then consulted in deciding which combination is the most desirable. In evaluating the possible assignments that can be made, RAMPS must also consider the indicated project completion dates, project delay penalties, and activity interrupt penalties.

Occasionally, these items override one or more control factors. This might occur, for example, when a project has a high delay penalty so that it becomes imperative from a cost standpoint to give priority to critical activities even though the free and total float control factors carry a relatively small weight. In another instance, an activity with an extremely low interrupt penalty may be interrupted even though the interrupt control factor is shown to be most important. However, the management control factors are used in scheduling every time period and will therefore dominate sched-
Four of the control factors, free float, total float, work continuity, and look-ahead, are used to evaluate individual activities that are competing for a resource during the time period being scheduled. These controls are used in deciding which activities are to be scheduled, and how many units of resource they are to receive.

The remaining two factors, number of jobs and idle resources, pertain to evaluation of all the assignments contemplated for the period. They ask the questions: "Does this assignment pattern minimize idle resources? Does it assure work on as many activities as possible?"

**Total Float**

The total float factor is intended primarily to place special emphasis on scheduling those activities with little or no total float. Therefore, the smaller the total float for an activity, the greater the emphasis placed on fulfilling its resource demands. Because activities on the critical path have no total float, a high total float weight forces early project completion because those activities on the critical path are given highest priority. After the critical activities have been served, activity priority decreases as total float increases.

**Free Float**

The free float control allows priority to be given to those activities with little or no free float. It therefore serves a two-fold purpose:

1. Expedites project completion by giving priority to activities on the critical path, and
2. Expedites activities with interfering float and thereby avoids bottlenecks that can occur when there is more than one critical path.

Because it gives priority to those activities that are likely to become critical in later time periods, the free float control can be an effective defense against delay in circumstances that demand that projects be completed as early as possible.

**Look-Ahead**

The look-ahead control provides a short-range guard against undesirable work stoppage or slow-down by giving priority to those activities upon whose completion several other activities are waiting. By means of the look-ahead control, RAMPS takes early preventive action against work build-ups later that could possibly delay completion of the project.

We can also see that the look-ahead control can be extremely powerful in the production of a schedule that calls for completion of the projects in a minimum amount of time. The overall effect is a maximum utilization of available resources in the production of a schedule that calls for a minimum project completion time.

**Work Continuity**

In every multi-project scheduling operation there are certain to be several activities that cannot be interrupted without incurring extra costs. Some activities might have high start-up costs; others might involve work with perishable goods which would be ruined if work were interrupted. In instances such as these, the work continuity factor is used along with activity interrupt penalties to show the importance of sustaining work on certain activities once they have been started.

In effect, a weight assigned to the continuity factor tells RAMPS that there are certain activities to be scheduled that should not be interrupted. The interrupt penalties assigned to these activities provide an indication of the relative costs of interrupting these activities. It is important to understand that activities with no interrupt penalties are most vulnerable to interruption; all activities are vulnerable to interruption, whether or not they carry an interrupt penalty, if the interrupt factor has no assigned weight.

When the possibility of interrupting an activity exists, RAMPS weighs the value of the interrupt factor and the individual interrupt penalties for the activities involved to determine the feasibility of interruption.

**Number of Jobs**

The purpose of the number-of-jobs control is to maximize the total number of activities scheduled during each time period. To achieve this purpose, RAMPS tends to schedule many activities at the slow-down rate to allow limited resources to be spread thinly over many activities.

The overall effect of this control is as follows:

1) many activities are started at their earliest
possible start dates, 2) speed in completing activities becomes secondary to concurrent work on all activities during a given time period, 3) the schedules for the projects are extended over a wider span of time because of the slower work rates.

Because the number-of-jobs control sacrifices project completion speeds for ability to work on the highest possible number of jobs per time period, it is most applicable in situations that require sustained, widespread work at the expense of fast completion of activities and projects.

Idle Resources

The idle resource control is concerned with utilizing a high percentage of the available resources during each time period. It is, of course, useful for emphasizing the high importance of keeping the number of idle resources at a minimum during each time period. In most cases, men, machines, and other resources represent a continuous cost, whether or not they are actually working. The aim of the idle resource factor is to "work" all resources at all times.

ANALYZING THE RESULTS

General Description

RAMPS produces two major reports, a work schedule for each project and a summary of units of resource used each time period by resource type. Analyzing these reports to determine whether or not the desired results have been obtained involves answering such questions as, "Have the desired completion dates been met? Have idle resources been kept to a minimum? When and where are the various resources used and how many premium units have been allocated?"

The Work Schedules

Figure 7 shows the work schedule for Project A and a breakdown of the various types of information contained in all RAMPS schedules. Although RAMPS internally interrelates the schedules for all projects, the printed schedules are produced separately for each project. This allows those who are interested in a particular project to receive only the information for that project.

The heart of the schedule is the right-hand portion which shows the time periods during which each activity is to be worked and the quantity of each resource allocated during each period. To the left are the event numbers, activity names, resources required, the three utilization rates, and amounts-of-work—all of which have been reproduced from the original data given to RAMPS.

![Figure 7. Output Schedules and Resource Allocation Summaries for Projects A and B.](from the collection of the Computer History Museum)
Note that each of these reports covers all allocations of a resource to all the projects.

When favorable answers appear, the reports form a springboard for setting the work plans in motion because they can be quickly turned over to supervisors, buyers, managers, and others throughout the organization who will be directly or indirectly responsible for getting the work done, obtaining the needed resources, and monitoring the progress of the work.

Perhaps of more importance, however, is how the reports are used to seek out flaws in the work plans that have caused the initial results to be disappointing or unsatisfactory. "Why was the target completion date missed? Should available resource quantities be increased? Decreased?" In large projects, there may be oversights in planning that create problems in the schedules. In many instances, they can be quickly corrected and the schedules put to immediate use; others will require extensive changes to the plan that make new schedules necessary.

It must be remembered, too, that because the information used by RAMPS is derived from the individual thinking of many people and based on estimates, it is fallible. However, one of the great advantages of RAMPS is that it can illuminate mistakes in planning before they are turned into wasted time, misspent funds, and misused manpower and materials.

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REFERENCES
