Information Report FF-X-67

December 1978

AIRPRO

AN AIR TANKER PRODUCTIVITY COMPUTER SIMULATION MODEL

AIR TANKER SYSTEMS

by

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This report is one of a series describing AIRPRO. Other reports in this series are:

The Fortran Program (Summary, Documentation),
Information Report FF-X-64, August 1977

The Equations (Summary, Documentation),
Information Report FF-X-66, January 1978

Validation
Information Report FF-X-68, December 1978

Application
Information Report FF-X-69, December 1978

ABSTRACT

This report examines air tankers from a systems point of view. The discussion begins by describing the fire control environment. Fire suppression is discussed from the resource management viewpoint. Emphasis then shifts to identifying the structure, components, resources, work process, objectives, and control of air tanker systems.

Three distinct air tanker resource management functions are identified: acquiring resources from the market, allocating resources to the field, and using resources to control fires. As the core of an air tanker system, air tanker utilization is examined in greater detail. Four utilization subsystems are identified: selection of resources and tactics, retardant delivery, retardant drop, and fire suppression. The system overview incorporates all the components which will ultimately be required to develop a comprehensive simulation model of the use of air tankers for wildland fire suppression.

RESUME

Dans ce rapport, l'auteur considère les avions-citernes du point de vue d'un système. L'étude débute par une description de l'environnement dans lequel s'effectue la lutte contre le feu. La suppression des incendies est examinée dans l'optique de la gestion des ressources. L'emphase est ensuite mise sur l'identification de la structure, des composantes, des ressources, du processus de travail, des objectifs et du contrôle des systèmes d'avions-citernes.

L'auteur a identifié trois activités distinctes reliées à la gestion des avions-citernes en tant que ressources, c'est-à-dire: l'acquisition des ressources sur le marché, la répartition des ressources sur le terrain et l'utilisation des ressources pour combattre les incendies. L'utilisation de l'avion-citerne, qui constitue le coeur du système, a été étudiée plus en détail. On a subdivisé le processus d'utilisation en quatre sous-systèmes, soit: la sélection des ressources et des tactiques, l'acheminement des retardants, le largage des retardants et la suppression du feu. Cette vue d'ensemble du système englobe toutes les composantes qui en fin de compte seront nécessaires à la mise au point d'un modèle de simulation détaillé de l'utilisation des avions-citernes dans la suppression des incendies forestiers.

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ACKNOWLEDGEMENTS

The author wishes to thank those without whose contribution, this project could not have succeeded. Without initial financial support by the FIRESCOPE project of the U.S. Forest Service Fire Laboratory, Riverside, California, the project might not have been started. Without the continued support of the Director of the Forest Fire Research Institute, Mr. D.E. Williams, the project certainly would not have been completed. To: Drs. Bruce Bare, Brian Mar, Robert Meir, Gerrard Schreuder and Stewart Pickford of the University of Washington, who gave freely of their time and advice, providing constructive suggestions throughout, thank you.

Without the considerable efforts of the typists, Mrs. Audrey Laing and Mrs. Sandra Cybulski, this report would not be readable. Finally, I would like to thank Mr. Neil Bruce, for finding all those little errors that everyone else seems to miss. Ultimately, the author accepts responsibility for everything contained inthis document, including all errors of commission or omission.

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A.J. Simard

I. Introduction

Fire management agencies throughout North America are facing increasingly stiff competition for a share of the public purse, while fire suppression costs are simultaneously rising. Further, spiraling resource values are necessitating improved fire control effectiveness in the face of increasing fire occurrence. None of these pressures is likely to moderate in the foreseeable future. There is only one solution to the dilemma - wildland fire suppression effectiveness will have to increase.

The traditional approach to increasing effectiveness has been to increase productivity through technological development. During the past 75 years, wildfire control technology has developed in three distinct phases. In the first 25 years, men and hand tools carried the bulk of the load. In the second 25 years, mechanical equipment such as pumps and bulldozers vastly increased the productivity of ground forces. In the last 25 years, the development of air tankers added a third dimension to fire control technology.

Each of the three phases is marked by several characteristics. The manpower phase was distinguished by relatively low productivity accompanied by low cost. Having few options available, the management function was relatively simple.

The mechanized phase witnessed significant increases in both productivity and cost. The manager was now concerned with simple infrastructure, in terms of roads and logistics support. The acquisition of new technology involved major expenditures and long-term decisions. The difficulty of the manager's task increased significantly but not insurmountably.

The addition of air tankers resulted in many changes to fire management. Air tankers are both the most effective and the most costly fire suppression resource available today. Of perhaps greater significance, however, the richness of the set of alternatives provided by air tankers requires sophisticated management systems, if effectiveness is to be maximized. Major irreversible capital expenditures are involved in air base construction and aircraft acquisition. The availability of thousands of different air tanker resource and tactic combinations precludes "seat-of-the-pants" optimization on individual fires, let alone an administrative region. The speed with which air tankers respond to fires adds a multiple fire dispatch compatibility. To compound the problem, air tanker productivity cannot even be measured directly. Clearly the manager needs help.

It should be readily apparent, that future increases in wildfire suppression effectiveness will come as much from improved management as from technological advances. This study represents an attempt to improve fire control management. Since, according to the preceding arguments, the most pressing need is with respect to air tanker system management, that is the focus of this effort.

This report will examine the use of air tankers for wildland fire suppression from a systems point of view. The structure and components of the system, the resources available to the system, as well as the work performed, and finally system objectives and control mechanisms will be considered. The discussion begins with a description of the fire control environment. It then considers the fire control function from the resource management viewpoint. Finally, air tanker systems are discussed in general and air tanker utilization in particular.

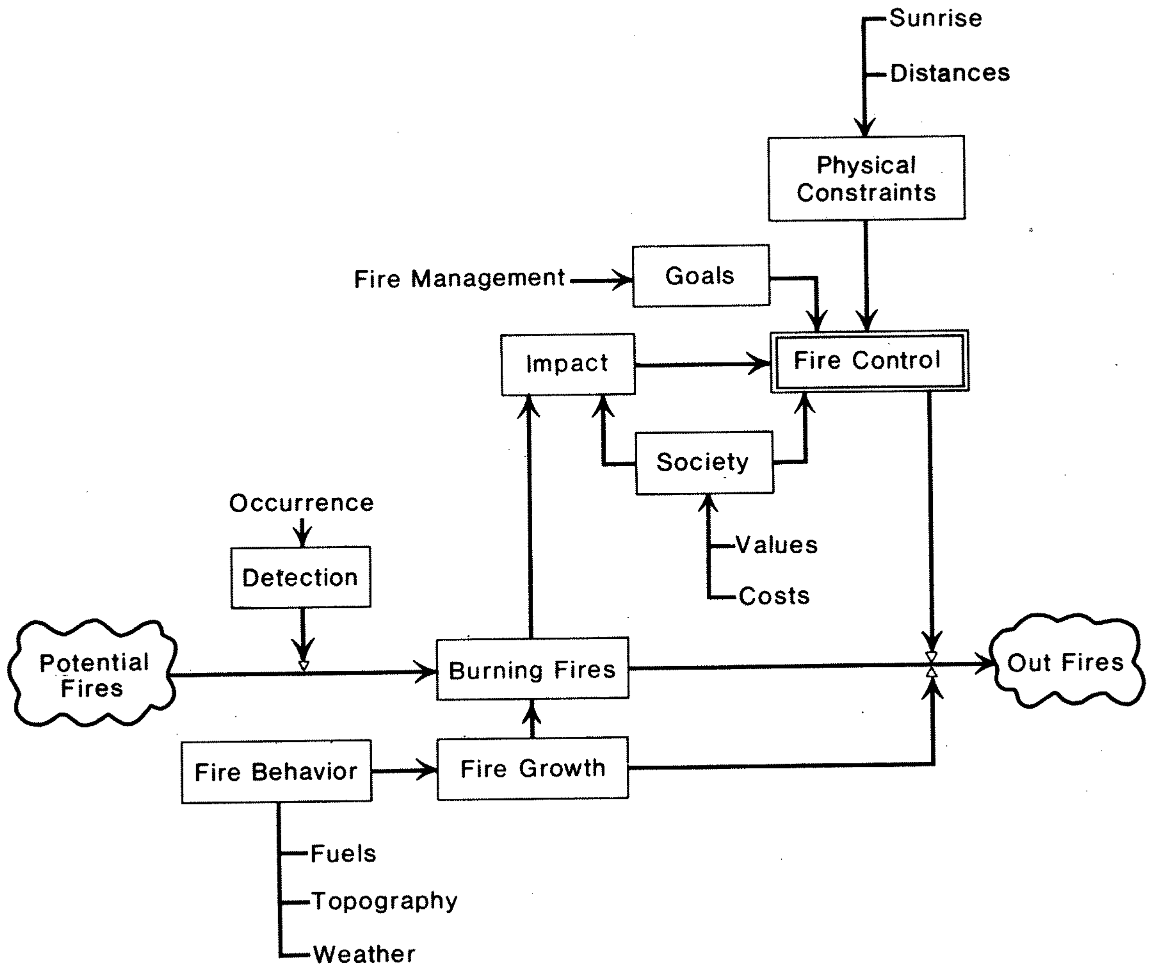
2. The Fire Control Environment

All systems exist within a hierarchy of systems. That is, every system is both a component of a higher-level system and its components are made up of lower-level systems. More specifically, air tanker systems are one component of wildland fire control which is, in turn, one component of wildland fire management. To insure compatibility of goals and meaningful results, the examination begins at the level of wildland fire control.

The first task is the deliniation of the boundaries of the system to be studied. That is, what is within the system itself and what are the significant aspects of the system's environment. Those aspects of the fire control environment considered significant to the anslysis of air tanker utilization are illustrated in Figure 1. It should be emphasized that Fig. 1 does not contain all aspects of the fire control environment as defined by an earlier study (Simard, 1977). Rather, it reflects a series of decisions which have eliminated many fire control environmental relationships which were considered not relevant to the present purpose.

The fire control environment is seen as a flow-through process. The key element in the process is the level of burning fires. Burning fires generate the demand for fire control activity through their effect on the impact component (area burned, costs, losses, etc.). As the level of burning fires increases or decreases, fire control activity responds correspondingly. The flow into burning fires is seen to originate in an infinite source. The rate of flow is controlled by fire occurrence which, for the present purpose can be further limited by fire detection. To analyse the use of air tankers, we do not need to know the causes of ignition, nor do we need to concern ourselves with the activity of wildland fires prior to detection. From the limited fire control point of view, fires which have not been detected do not exist and, therefore, generate no demand for activity.

Figure 1 The Wildland Fire Control Environment



At the moment of detection, a fire of a certain size and with a variety of behavioral characteristics is added to the burning fires component. Its behavioral characteristics (primarily spread rate and intensity) respond dynamically to variations in three environmental factors: fuels, topography, and weather. Fire behavior controls fire growth which, in turn, increases the level of burning fires. While fire extinguishment (negative fire growth) results in some reduction in the level of burning fires, the primary factor controlling the flow from burning fires to the infinite sink is fire control. Note that fires which are allowed to burn, implying a desirable impact, are not part of the set of fires relevant to air tanker operations.

Fire control receives its goals from the wildland fire management system of which the former is a part. The goal of fire control is defined from the theoretically defensible economic efficiency point of view. That is, the fire control system will be efficient, in an economic sense, if it maximizes NPV:

$$NPV = B - C - D \qquad (1)$$

where: NPV = net present value of a fire,
B = net present benefit,
C = present value of suppression cost, and
D = net present damage.

The many ramifications of Eq. 1 will not be discussed here. They have been considered at length elsewhere (Simard 1976, 1978). Suffice it to say that benefits and damage arise from the interaction of burning fires and the impact component, coupled with resource values which are dictated by society. Suppression costs, also dictated by society through the marketplace, affect fire control directly. Finally, wildland fire control is directly affected by certain physical constraints such as sunrise, sunset, and travel distances.

Simple as it may appear, the eighteen components shown in Fig. 1 constitute a complete description of the environment which affects the air tanker utilization component of fire control. From a systems point of view, there is little to be gained by disaggregating the environmental components down to the level of individual variables. Relationships tend to be primarily technical and, to varying degrees, documented in the literature. Since, by definition, a system cannot affect its environment, lower-level casual relationships and interactions do not need to be considered. Only the output of the various processes need be known, so that they may be used as stimuli to the system being analysed. We will, therefore, turn our immediate attention to wildland fire control, after which air tanker systems will be considered in some detail.

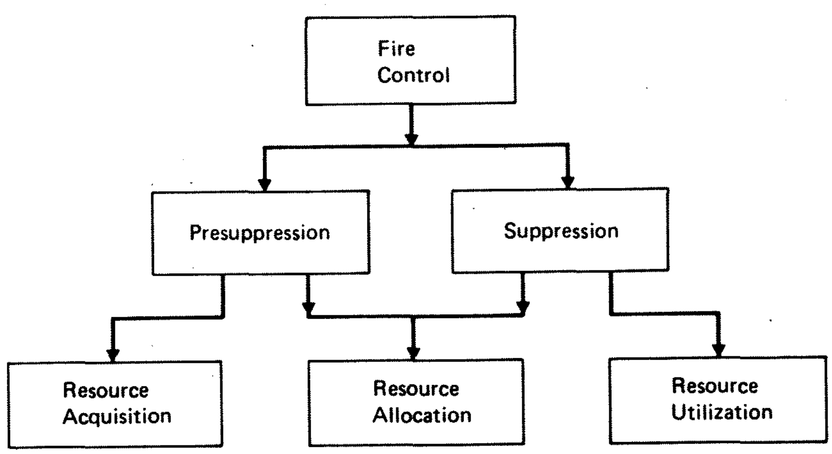
3. Fire Control

Fire control is commonly divided into two activities: presuppression (planning and organization activities undertaken prior to the detection of a fire) and suppression (control activities undertaken after a fire is detected). There is an intimate relationship between the two, in that very few suppression activities can be undertaken without advanced preparation. The use of air tankers is an excellent case in point. In order to assure the availability of air tankers when a fire is detected, aircraft, pilots, and support logistics must be contracted for at the beginning of a season.

Unfortunately, the traditional terms tell us little about the nature of the processes involved. Hence, they offer little in the way of suggestions for an appropriate analytical approach. It would be more useful if fire control were disaggregated on the basis of the various processes of interest. There are many disaggregation schemes which could be used. Since air tankers are a resource, resource management is an appropriate point of view from which to consider the fire control system.

There are three basic resource management functions: acquisition, allocation, and utilization. In essence, the fire management system must get the resources it needs from the market place; put the resources where they are likely to be needed; and finally, use the resources to control fires. The relationship between these functions and the traditional fire control activities are shown in Fig. 2. The remainder of this section will consider each of these functions in some detail.

Figure 2 **Relationship Between Traditional Fire Control Activities and Resource Management Functions**



A. Resource Acquisition

The objective of resource acquisition is to acquire a mixture of resources to enable the fire management system to operate efficiently. In general, this means that given a fixed budget, the nature of the resource mix acquired should be such that overall productivity will be maximized. A mathematical expression of the objective function for the resource acquisition subsystem can be defined in terms of marginal cost and productivity:

$$(2) \qquad \frac{Cm_{r1}}{Pm_{r1}} = \frac{Cm_{r2}}{Pm_{r2}} = \cdots = \frac{Cm_{rm}}{Pm_{rm}}$$

where: $r_1, r_2, r_3,$ = various specific resources,
Cm = marginal cost, and
Pm = marginal productivity.

Table 1 illustrates a portion of the fire control resource hierarchy. Each fire control subsystem needs every type of resource - fixed assets, equipment, manpower, and expendables. Of greater significance, however, is the fact that there are more similarities within a resource type than between types. In other words, from a resource acquisition point of view, air tanker bases have more in common with roads and trails than they do with air tankers themselves. This is in contrast to the point of view of the operating system, where one type of resource cannot function without the other. Thus, analysis of resource acquisition within a subsystem entails four distinctly different problems. On the other hand, it is likely that techniques used to analyze the acquisition of one type of resource for one subsystem will be reasonably adaptable to the analysis of the acquisition of a similar resource type within another subsystem.

Table 1 FIRE MANAGEMENT RESOURCE HIERARCHY

	Type of Resource			
Subsystem	Fixed Assets	Equipment	Manpower	Expendable
Men	Camps - Trails	Trucks	Crews	Food
Equipment	Roads	Bulldozers	Operators	Diesel Fuel
Air tanker	Air tanker bases	Air tankers	Pilots	Retardants

Capital (in the form of a fire management budget) has not been included in Table 1. While capital is, in fact, the ultimate resource through which the other resources are acquired, it is clearly different from the remaining four. It is acquired by a higher system level. The productivity of capital per se is zero. It is the resources which are acquired with capital that have physical productivity. Capital is therefore assumed to be given at this system level.

There are a number of characteristics which could be used to describe resources to illustrate the differences between the four types.

- The expected life span of the resource. Another way of expressing this is the time span of the acquisition decision. Maloney and Potter (1974) considered this characteristic in some detail. Long range decisions are generally made at the highest system levels. They often reflect non-technical, policy, political, or administrative consideration. Short range decisions, on the other hand, are made at low system levels in response to fairly immediate technical problems.

- Degree of constraint. A highly constrained system is far easier to analyze than one which has few constraints placed on it. This is related to the richness of the decision alternatives available to a system. High level, and hence complex, analyses tend to be associated with far ranging sets of alternatives.

- Difficulty of measuring productivity. The more closely associated a resource is to the ultimate output of a system, the easier it will be to measure productivity. As the difficulty of measuring productivity increases, the need for close consultation between the analyst and the manager becomes increasingly important, if research results are to be applied.

- Decision flexibility. Highly flexible decisions justify little in the way of sophisticated analysis as errors are readily correctable. Irreversible or permanent decisions must be weighed very carefully in advance.

- Cost per unit of resource. As resource costs increase, the degree of analysis which can be justified increases correspondingly.

Table 2 summarizes the relationship between the four resource types and the above characteristics.

It can be seen that in the case of fixed assets, the time span is on the order of several years; decisions are loosely constrained; productivity measurement is difficult; there is little flexibility; and the cost per unit of resource is high. Conversely, expendable resources involve short term, highly constrained decisions; productivity measurement is direct; flexibility is high; and costs are low. Clearly, totally different analytical approaches are needed for problems at these opposite ends of the resource spectrum.

As indicated in Fig. 3, the acquisition process itself is relatively straightforward. For all resources under consideration, marginal cost and marginal productivity are compared and a desired resource mix established. Then, a purchasing or rental process acquires the desired resource from the market place within the constraint of a budget. Additional resources can be made available to the system through cooperative

Table 2 CHARACTERISTICS OF THE VARIOUS TYPES OF RESOURCES

	Fixed	Equipment	Manpower	Expendable
Time Span	Many years	Few years	1 day - few years	1 day - 1 year
Constraints	Few	Moderate	Many	Many
Productivity Measurement	Difficult	Intermediate	Intermediate	Direct
Flexibility	Nil	Low	Moderate	High
Cost	Very high	High	Moderate	Low

agreements with other agencies. The entire process results in a resource mix available to the system.

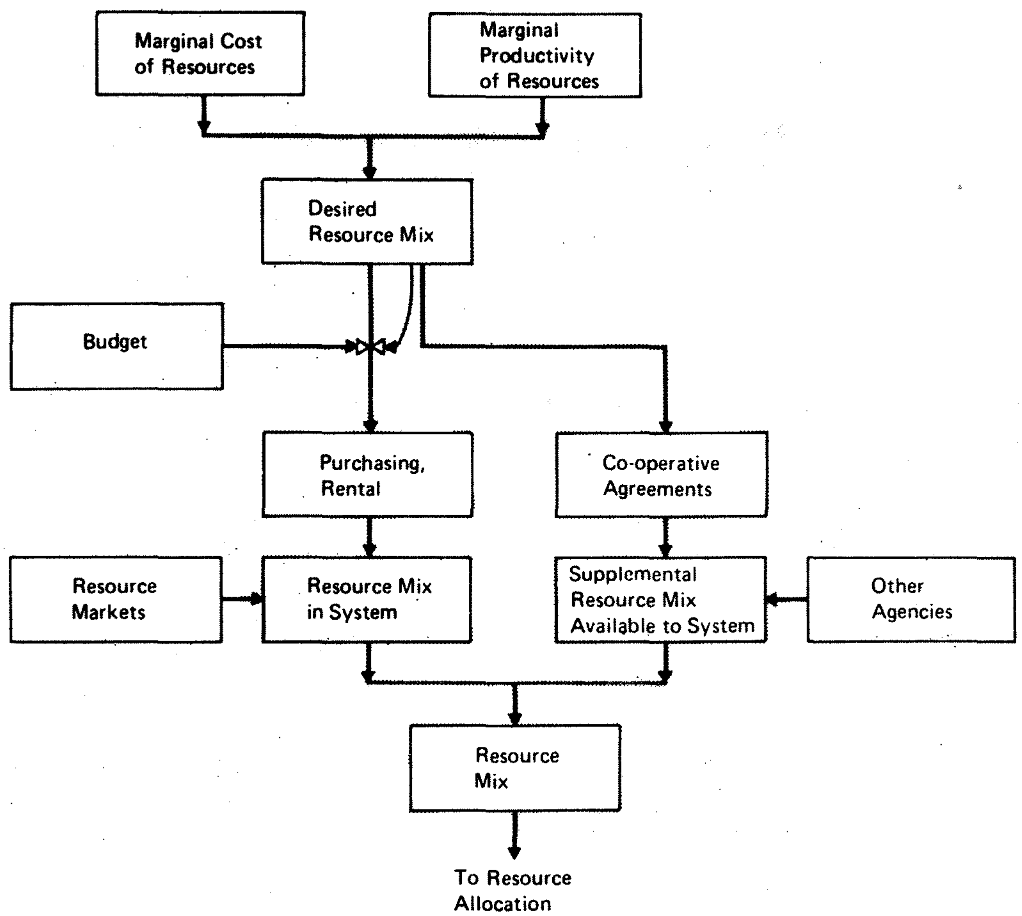
From a systems point of view, this process is relatively simple. The major difficulty, which, by and large, remains to be overcome, is the determination of resource productivity. Without a quantitative measure of productivity, quantitative analysis are not possible. Thus, although resource acquisition precedes the other resource management functions in an operational sense, it must follow the other functions in an analytical sense. We are drawn, therefore, to the next function - resource allocation.

B. Resource Allocation

The fire management system now has a mixture of resources available to it, adding a major constraint to the system. These resources must be allocatedin such a way that they will do the most good for the system as a whole. Thus, the objective of resource allocation is to allocate the available resource mix in such a way that system productivity is maximized over the planning period relevant to a specific allocation function.

Analytically, we are concerned with allocating a mixture of scarce resources to a variety of tasks or locations. This is a type of problem particularly well suited to a linear programing formulation. A general objective function of the form:

Figure 3 **The Resource Acquisition Process**



(3)

$$\text{max. } Z = \sum_{j=1}^{n} \sum_{k=1}^{m} c_{jk} x_{jk}$$

$$\text{subject to: } \sum_{j=1}^{n} \sum_{k=1}^{m} a_{ijk} x_{jk} \leq b_i \; ;$$

$$x_{jk} \geq 0$$

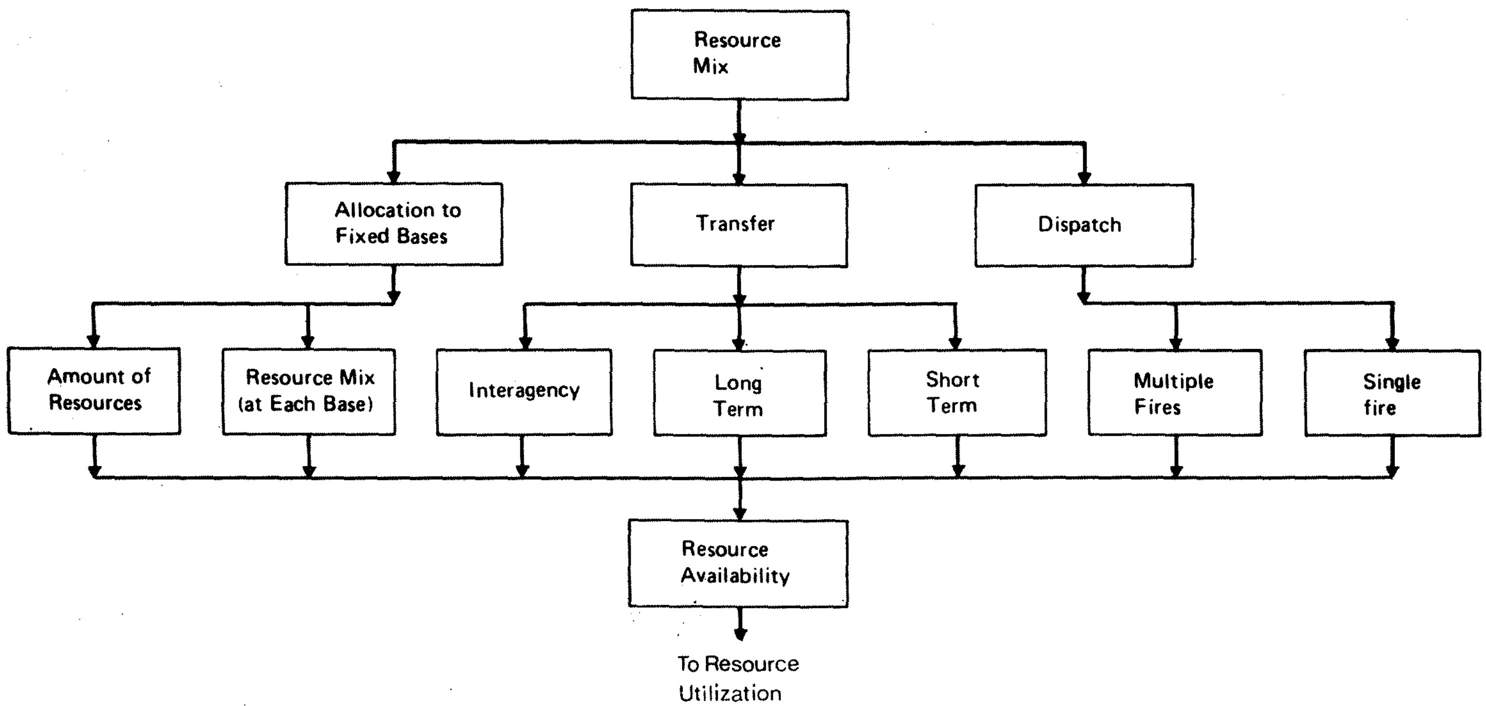
where: Z = system productivity,
Cjk = productivity of resource j at location k,
Xjk = quantity of resource j at location k, and
a,b = technical coefficients

would be applicable to most resource allocation problems.

A solution to Eq. 3 would allocate all available resources so as to maximize system productivity. Obviously, a detailed analysis of a real world problem would have a significantly more complex formulation. Additional constraints could readily be added, depending on the needs of the system. For example, every location could be required to have something allocated to it; no more than a specified percent of the total resource could be allocated to any single location, etc. Alternatively, for some applications such as transfer, the above could be reformulated as a transportation problem with cost minimization as the objective. Note that it is not possible to maximize productivity and minimize cost simultaneously with linear programing - one or the other must be held constant.

Resource allocation involves a number of complex functions. The allocation hierarchy is illustrated in Fig. 4. Three general allocation functions are indicated: allocation to fixed bases, transfer, and dispatch. The reasons for differentiating between allocation functions are the same as those for differentiation between the four types of resources. For example, allocating resources to fixed bases involves: decisions with time spans of one or more seasons, few constraints, limited flexibility, substantial investments, and expected productivity is relatively difficult to analyze. Single fire dispatch decisions, on the other hand, tend to have time spans from a few minutes to a few hours, are highly constrained, relatively flexible, do not involve major financial commitments, and are directly related to system output. Transfer decisions cover the full range between the two extremes.

Figure 4 Resource Allocation Hierarchy



As indicated in Fig. 4, there are seven specific allocation functions: the amount and mixture of resources allocated to each base; interagency, long-term, and short-term transfer; and multiple and single fire dispatch. Each is a distinct problem, requiring individually tailored analytical techniques. To consider each function in detail would result in a lengthy discussion which would contribute little to our utlimate objective. Resource allocation will, therefore, not be discussed further.

Whether a linear programing formulation is used, as in Eq. 3 or an economic formulation such as Eq. 2 is adapted to the allocation function, one fact stands out - resource productivity must be known before a quantitative analysis of resource allocation problems is possible. Thus, as was the case previously, although allocation must precede utilization in an operational sense, the analytical order must be reversed. Only after the utilization function is understood, will it be be possible to proceed upwards analytically through the remainder of the system.

C. Resource Utilization

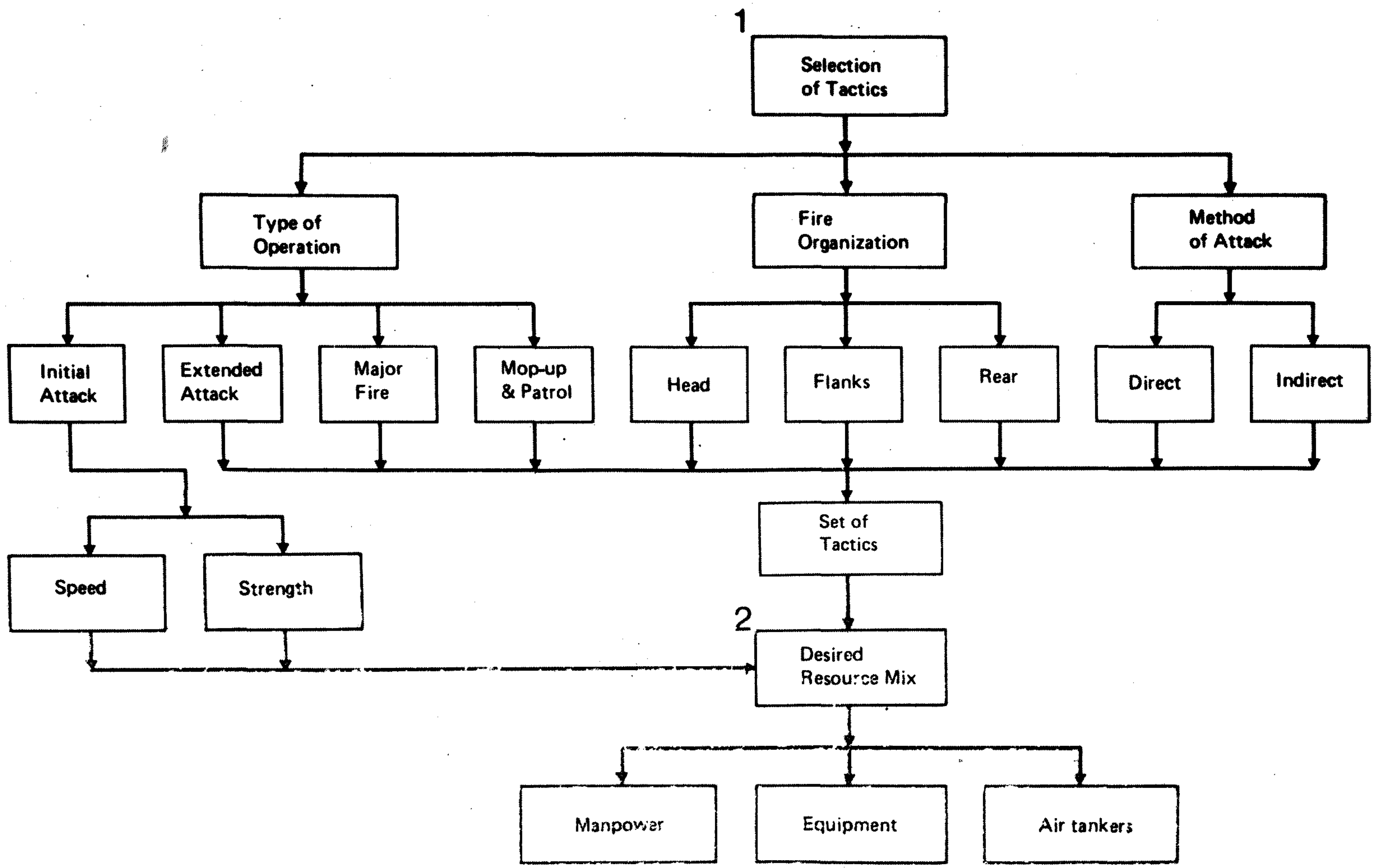
The fire manager now has a specific set of resources available to him. He must employ these resources to control specific wildland fire - a moderately constrained situation. This is the heart of fire control. Resource utilization will be considered from two different viewpoints: the decision network and the physical fire suppression process.

There are a myriad of decisions made during the course of controlling a fire. From this universe, a set of decisions of primary interest to our purpose has been selected. These have been grouped in a hierarchy and are illustrated in Fig. 5. There are two basic types of decisions to be made. Resources must be selected and the manner of their use (tactics) must be determined. While for convenience of illustration, Fig. 5 suggests a sequential process, these decisions are interdependent and may be made simultaneously.

For each of the preceding decisions, there are a large number of choices available to the manager. For computational convenience only a limited set, spanning the range of alternatives, is considered here. This is essential, as the effect of every decision depends on every other decision with which it is associated.

As an example of the interdependence of the decisions, it has long been recognized that elapsed time between detection and initial attack is an important factor in determining suppression effectiveness. In a specific situation, the relative importance of travel time is related to the fire environment and the strength of the attack force. The manager can use a helicopter to decrease travel time or send a larger crew to achieve the same

Figure 5 **Resource Utilization Decision Hierarchy**



results. Every decision must be considered in relation to the overall goal of the fire control system. This interdependency is significant from an analytical point of view, in that complete enumeration of all possible outcomes is often the only course available. If the set of alternatives to be considered is not limited at the outset, a problem very quickly becomes unmanageable.

To insure compatibility with the fire management system, the overall objective of resource utilization would be to select a set of tactics and utilize a mix of resources such that the cost of suppression plus the economic loss caused by a fire is minimized (Eq. 1). Thus, the objective function discussed at the highest control level also applies here. The main difference is that, at this level, we are concerned with a specific set of resources made available by the allocation function and a specific fire. The increase in constraints renders the problem somewhat more manageable (in theory at least).

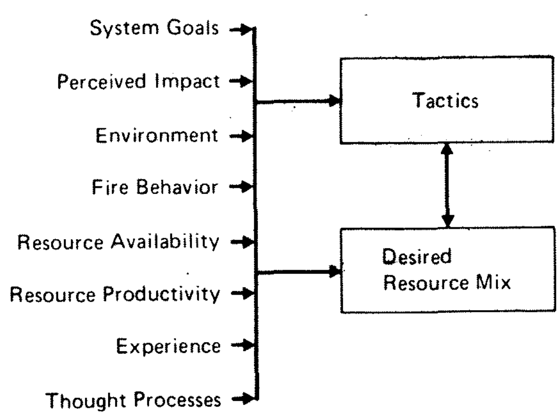
Simard (1976) discussed a number of real world problems, such as indivisibility of resources, imperfect knowledge, and risk, which require modification of the above objective. Further, the fire manager may not be particularly concerned with resource costs. This is partially a reflection of the urgency of a fire control situation, but also a reflection of the budget process. Fire fighting costs are often paid from an emergency budget, from which virtually unlimited funds can be drawn. On the other hand, the manager is vitally concerned with productivity. He normally selects tactics in such a way that each resource will be used most effectively and so that the fire will be controlled as quickly as possible. In a theoretical sense, the manager may or may not optimize his selection of tactics with respect to the overall system. In a practical sense, without benefit of hindsight, perfect information, and a system to process that information, it is unlikely that a theoretical optimum could ever be achieved. In addition, the manager has to live with fires that escape, whereas the analyst does not. Thus, the manager will, with legitimate reason, tend to use more than the optimal amount of resources actually needed to control a fire.

The extent to which real-world imperfections need be considered in an analysis of fire control systems to insure validity is open to debate. On one hand, the above factors are not likely to significantly affect relative results. Thus, if the primary application were in the planning process, many real world problems could be ignored as, in fact, they are today. If, on the other hand, the primary application were in the form of real time, computer assisted dispatch, many considerations specific to an individual fire would have to be incorporated, since absolute results would be required. The model will emphasize theoretically correct solutions. These can be subsequently modified as necessary to fit field conditions.

As suggested previously, there are two types of decision determine how the fires are to be controlled and select a mix of resources to perform the control function. Resource selection has been discussed under the acquisition function. It will, therefore, not be considered at this point, except to note that at this level the manager may only select from the set of resources made available by the allocation function.

The decision process involves anticipating the impact of fire; determining the deviation of that impact from the goals of the system; and responding in such a way so as to reduce the deviation. To accomplish this involves the integration of impact, environmental, fire behavior, resource availability, and productivity information in such a way that optimal tactics and resources for a particular fire can be selected, based on the goals of the system. Fig. 6 illustrates the inputs to the decision process. Given the current state of knowledge, the technical challenges alone are nearly insurmountable. To further complicate the problem, that quantitative information which is available is combined with the experience and subjective thought processes of the manager and a decision is reached. Fortunately for our purposes it is not necessary that the decision process itself be understood. Only the output of the process need be known, not the mechanisms whereby it is generated.

Figure 6 **Inputs to the Decision Process**



The resource utilization process is illustrated in Fig. 7. The manager interacts with the allocation function and a mix of resources are dispatched to the fire. The resources are transported to the fire and, after a travel delay, suppression begins. Productivity for each resource depends on several factors: resource characteristics, topography, fuels, fire behavior, and weather. Resource productivity in combination with the set of tactics, results in a fire suppression rate which, in turn, reduces the burning fire level. Finally, the combination of resource productivity, fire suppression effectiveness, and an evaluation criteria yields the value of resource use, or resource effectiveness. As has been mentioned, many decisions at higher system levels are based, in considerable part, on resource productivity realized at the utilization level. In other words it is through analysis of the utilization level that resource productivity can be determined.

4. Air Tanker Systems

As a fire suppression resource, air tankers have some interesting and unique characteristics. They are, if properly utilized, the most effective initial attack resource available. In addition, they are both highly mobile and flexible. As with all things, however, the manager cannot avail himself of the desirable attributes of air tankers without paying a penalty.

They are the most costly resource currently employed in fire control operations. Further, the richness of the set of alternatives provided by air tankers results in a far more complex decision hierarchy than is the case for other fire control resources. The high contrast between effectiveness and cost, as well as flexibility and complexity, implies that sophisticated management systems are required, if benefits are to be maximized. This section will consider air tanker systems in general and air tanker utilization specifically. The primary objective is to provide background for the air tanker productivity model to be developed in subsequent chapters.

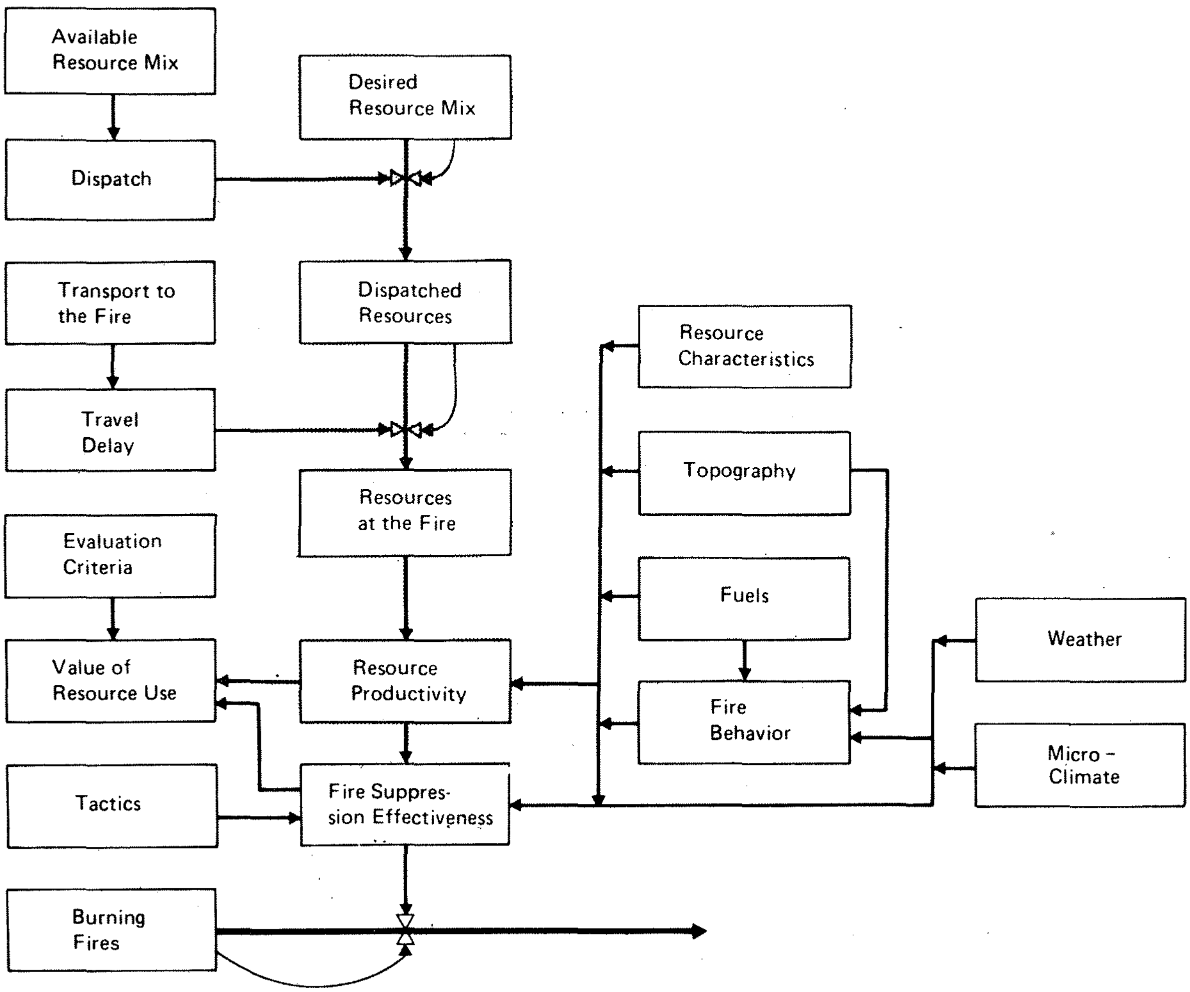
Air tanker systems, as defined in this study do not include the use of aircraft for detection, crew transport, logistics, or intelligence gathering. To the extent that some aircraft are multi-purpose, this study is incomplete. It was felt, however, that the air tanker problem is, in itself, sufficiently complex that to include any other consideration would run the risk of making the analysis unmanageable. Thus, another aspect of the system boundary has been delineated.

The objective of the air tanker system is to acquire, allocate, and utilize air tanker resources in an efficient manner and, in conjunction with other fire suppression resources, to achieve the goals of the fire control system. Mathematically, an air tanker system will be operating efficiently with respect to fire control if:

(4) $$\frac{Cm_a}{Pm_a} = \frac{Cm_r}{Pm_r}$$

where: a = air tanker resources and
r = all other resources combined.

Figure 7 **Resource Utilization**



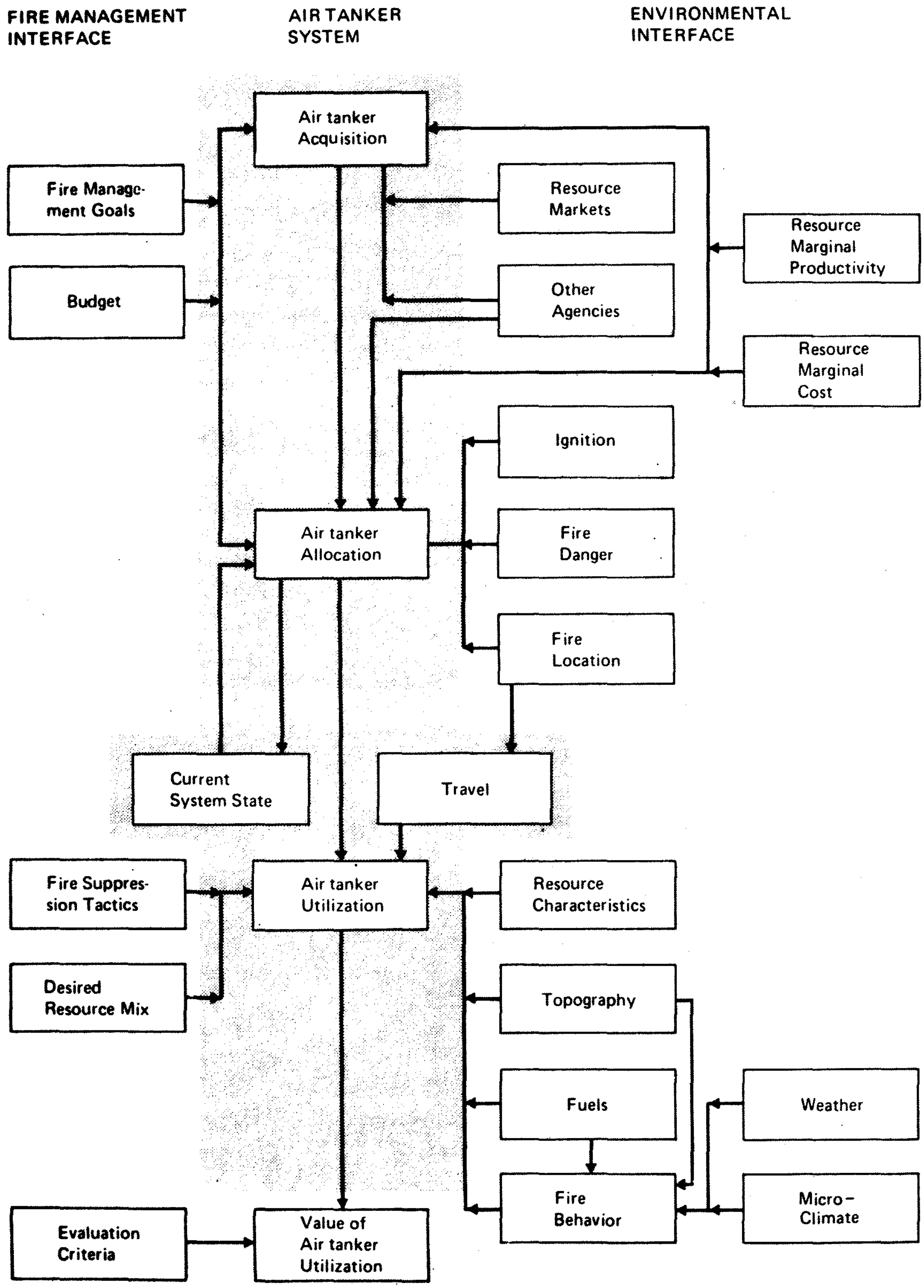
In other words, in quantitative terms, the objective of the air tanker system is to equate the Cm/Pm ratio for air tankers with the Cm/Pm ratio for all other resources.

A generalized air tanker system is shown in Fig. 8. At this level, the air tanker system is a simple sequential flow-through system. As with fire control, there are three resource management functions associated with air tanker systems: acquisition, allocation, and utilization.

A. Air Tanker Acquisition

The object of air tanker acquisition is to acquire air tanker related resources to enable the air tanker system to operate efficiently with respect to fire control system. Equation 2 applies to the case of specific resources with the addition of constraint. To function, an air tanker system needs a minimum of every category of resource. There has to be at least one base, one air tanker, a pilot and crew, some retardant, and logistic

Figure 8 **An Air tanker System**



support. Beyond the minimum it becomes feasible to consider one type of aircraft versus another or additional bases versus additional aircraft, by applying Eq. 2 directly.

A hierarchy of air tanker related resources is given in Table 3. The following is a list of air tanker resource decision alternatives.

1) Air Tanker Bases

There are three broad air tanker basing concepts currently used in North America today.

- Centralized bases. One or a few large, completely self-sufficient bases, each with extensive facilities.
- Principle and satellite bases. Scattered self-sufficient bases, each with complete but not extensive facilities. Each principle base has a set of satellite bases associated with it, generally with mixing facilities only.
- Small bases. Many small bases scattered throughout the protected area. These bases generally have little or no maintenance facilities and limited or portable mixing facilities. There is generally one large central base which supports the small bases.

The above concepts are a composite of many individual basing decisions.

- How many bases should there be?
- What type of operation should the bases support (land-based, water-based, amphibious, helicopter)?
- Where should the bases be located?
- What type of facilities should each base have?

Maintenance: complete facilities, minor repair, none.

Mixing: capacity of mixing system, storage capacity, type of retardant.

Logistics: storage capacity, resupply system.

2) Air Tankers

The acquisition of air tankers is closely related to the establishment of bases. The two must be compatible if the system is to function efficiently. Thus, a truly optimal solution will require that both types of resources be considered simultaneously.

Table 3 AIR TANKER RESOURCE HIERARCHY

Fixed Assets

- Air Tanker Bases
  - Number
  - Type of Operation
  - Location
  - Facilities
    - Maintenance
    - Mixing
    - Logistics

Equipment

- Air Tankers
  - Number
  - Type
  - Characteristics
    - Aircraft
    - Air Tanker

Manpower

- Pilots
- Maintenance Crew
- Mixing Crew
- Air Attack Coordinator
  - Number
  - Experience
  - Training
  - Abilities

Expendable Resources

- Retardant
  - Amount
  - Type
- Logistics
  - Gas and Oil
  - Spare Parts

- How many air tankers are needed?

- What type of air tanker should be acquired (land-based, water-based, amphibious, helicopter)?

- What characteristics should the air tankers have? These can be divided into two categories: a) those related to the aircraft itself, and b) those specifically related to air tanker operations.

  a) Aircraft characteristics

  - Speed (mph)
  - Range (miles)
  - Endurance (hours)
  - Take off distance (feet)
  - Rate of climb (feet/min)
  - Maneuverability (relative to other aircraft)
  - Circuit time (load, takeoff, drop, land - in minutes)
  - Safety (number of engines, design load factor, age, etc.).

  b) Air tanker

  - Retardant tank capacity (gallons)
  - Retardant tank configuration (single, multiple, number of tanks)
  - Drop patterns (length and width in feet)
  - Drop accuracy (expected percentage of on-target drops or average error).

3) <u>Manpower</u>

Table 3 lists a number of different types of personnel needed to operate an air tanker system. A set of questions must be answered with respect to each type.

- How many are needed?

- What experience is needed?

- How much training is needed?

- What are the natural and administrative abilities and limitations? (limitations on flying or working hours, how much work can an individual reasonably be expected to perform, etc.).

4) <u>Expendable Resources</u>

- How much and what type of retardant is required (water, short-term, long-term)?

- How much gas and oil will be needed?

- How extensive should the parts inventory be?

Some of the above questions are easily answerable while others require major research efforts. It is sufficient for our purpose to list the set of decision alternatives available to the manager. We need not consider the mechanisms whereby individual acquisition decisions are made to consider the effect of the decision on the utilization function. Thus, air tanker resource acquisition need not be considered further.

Only limited air tanker acquisition research has been undertaken to date. In a series of reports, Stade (1966-68) attempted to determine adequate fleet size for several Canadian provinces, based on using the CL-215 air tanker. Newburger (1966) determined the "optimum" air tanker size and fleet requirements for the province of New Brunswick. Martel (1971) determined the number of TBM's that should be based at Dryden, Ontario. In each case, only one aircraft and type of operation were considered - obviously highly constrained analysis, given the decision alternatives available to the manager. In all cases, simulation was the primary analytical technique. Newburger and Martel used primarily stochastic models while Stade combined stochastic and deterministic mathematical elements.

It should be pointed out that there is no lack of qualitative and descriptive literature. Virtually every organization in North America that uses air tankers has published numerous articles, reports, and surveys describing their operations. This information provides a wealth of data on what is being done and how it is being done. Such information is basic to understanding how an air tanker system operates, but is of little help in quantifying air tanker systems.

B. Air Tanker Allocation

Conceptually, air tanker allocation differs little from resource allocation in general. Those differences which are apparent primarily reflect the considerable flexibility provided by air tankers. For example, allocating air tankers to fixed bases is a relatively flexible decision in that changes can be readily made during the fire season. Because of high travel rates, transfer becomes a major operation, as air tankers are frequently moved long distances in response to anticipated demand.

Since air tankers respond quickly over long distances and equally quickly complete a mission, one air tanker base normally has a considerably larger area of responsibility than a ground station. As a result, multiple fire dispatch becomes common-place relative to ground forces. In addition, air tanker dispatch is normally the prerogative of a higher fire control administrative level than the dispatch of ground forces. Differences between the allocation of air tankers and resources in general are of degree, however, not of kind. Since there is little to be gained by repeating the general allocation discussion, air tanker allocation will not be considered further.

A review of the literature relative to air tanker allocation is more productive than was the case for acquisition. Greulich (1967) used linear programing to develop a function relating retardant delivery to daily transfer expenditures for three California air bases. Olson (1972) used simulation to minimize response time and flying distance from several Arizona air bases Maloney (1972) used linear programing to optimize the allocation of three air tanker types to twelve air bases in California. His model included a measure of relative air tanker efficiency (in terms of retardant delivery). Simard (1973) used simulation to study the temporal dynamics of a theoretical interagency air tanker transfer system. That study used the minimization of response and flying times as primary objectives. Renton et al. (1974) used an implicit enumeration technique to allocate air tankers to air bases in California while minimizing allocation cost. His model was constrained such that minimum levels of protection were afforded at each base. Finally, Greulich (1976) used linear programing to extend previous research by optimizing the combined seasonal and daily allocation of aircraft to bases. No doubt, the existence of mathematical techniques which are well suited to the allocation problem, as well as their relative ease of application has encouraged research along these lines.

The next topic in the sequence is air tanker utilization. Since it is the focus of the current research effort, utilization will be covered in a separate section in considerably greater detail than previous topics.

5. Air Tanker Utilization

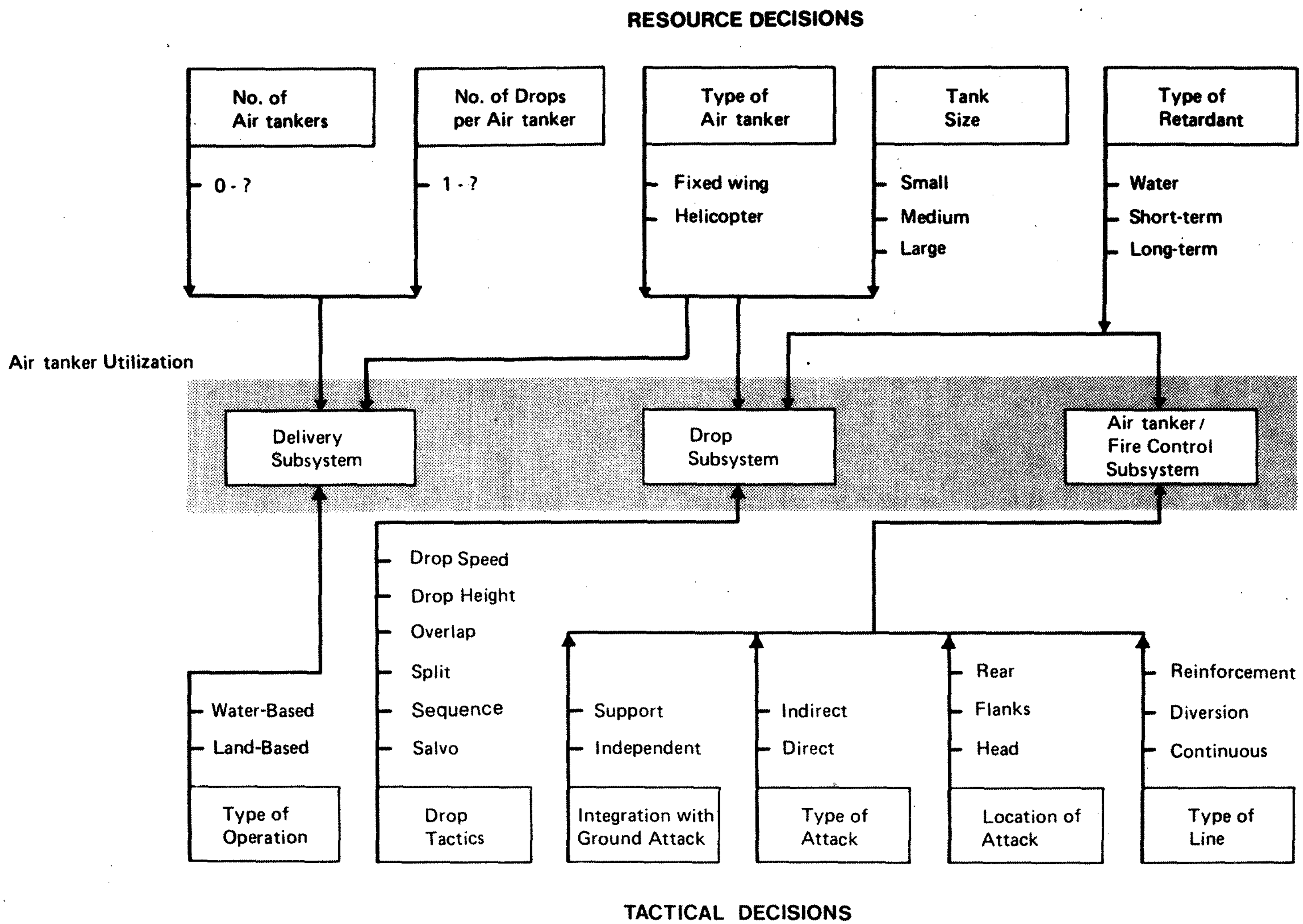
A. The Decision Function

At this system level, the manager has available to him a specific set of air tanker related resources. His objective is to utilize these resources, in conjunction with other resources, to efficiently control a specific wildland fire. As was the case for resource utilization in general, the objective would be to minimize the cost-plus-loss of a fire (Eq. 1). There is a set of decisions that have to be made with respect to air tanker utilization. These can be divided into two classes - resource decisions and tactical decisions. The decision hierarchy is shown in Fig. 9.

There are 11 decisions which have to be made.

1) Number of air tankers - anywhere from zero to a maximum number may be used on any fire. A limit is imposed by the maximum rate at which retardant can be dropped. The limit can range from

Figure 9 **Air tanker Utilization Decision Hierarchy**



as few as four or five drops per hour in the most difficult situations, to as many as twenty drops per hour in straightforward situations.

2) Number of drops per air tanker - this can range from one to a maximum which is limited by factors such as sunset, pilot and aircraft endurance, in combination with circuit time.

3) Type of air tanker - only two broad classes are considered here - fixed wing and helicopter.

4) Tank size - while the fifteen aircraft types currently in use in Canada provide practically a continuum of sizes, a three-class differentiation is considered adequate for general management decisions. The class definitions are:

- Small (less than 750 Imp. Gal.);
- Medium (750 - 1,500 Imp. Gal.); and
- Large (1500 Imp. Gal. or more).

5) Type of retardant - while there are specific brand namesof retardants, the range of characteristics Within a class is sufficiently small that no differentiation is necessary. Three types of retardants will be considered: water, short-term, and long-term.

6) Type of operation - the essential characteristic of a water-based operation involves scooping water from the surface of a lake. When lakes are close to a fire, very high delivery rates can be attained. When there are few lakes, the benefits of fast loading are decreased. Land-based operations involve returning to air bases for each load of retardant. Delivery rates tend to be lower but effectiveness may be increased by the use of more effective retardants. The decision is differentiated from air tanker type because although water- and land-based aircraft are obviously constrained to one type of operation, both helicopters and amphibious aircraft can function either on water or land.

7) Drop tactics - there is quite a variety of drop tactics or release sequences that could be employed.

- Salvo - dumping the entire load at once.
- Sequence - dumping individual tanks sequentially with from a tenth of a second to one and a half seconds between releases.
- Split - dropping individual tanks separately - i.e., a separate approach and drop for each tank. This will increase total length of line per load but extract a cost in terms of increased drop time and reduced holding ability.
- Overlap - drop effectiveness can be increased by overlapping successive drops.

- Drop speed - increasing drop speed should increase pattern length and decrease retardant concentration. Reducing drop speed should have the opposite effect.

- Drop height - increasing drop height will, at first, increase pattern length but after an optimal height is reached, further increases are offset by retardant loss and pattern lengths decrease.

8) Integration with ground attack - airtankers can either work independently or in support of ground forces. When both are on a fire at the same time, productivity is generally maximized by having air tankers control the head while ground forces attack the rear and flanks. Further, it is generally agreed that the most effective use of air tankers is in initial attack where they delay the fire until ground forces arrive. It must be emphasized that air tankers do not extinguish fires by themselves. They drop retardant which delays the advance of a fire until ground forces can physically construct a line.

9) Type of attack - indirect (parallel to, but some distance ahead of the fire front) versus direct (normally the load is dropped half on and half in front of the fire).

10) Location of attack - the typical sequence is head, flanks, and rear. There are two principle variations: a flanking attack where, because the head is too wide or intense, an attempt is made to pinch it off; and a partial attack where just the head, or head and flanks are held by air tankers.

11) Type of holding line

- Continuous - the most common and most effective line is laid continuously from a secure anchor point.

- Diversionary - this is an intermittent line which could be laid for any of several reasons, for example: to temporarily cool hot spots or protect particularly valuable or potentially dangerous areas and/or equipment trapped by the fire.

- Reinforcing - this is strictly a support operation where the intention is to reinforce a ground line which is considered weak. It could also involve fireproofing potentially dangerous areas on either side of the line.

A more detailed discussion of the above decision set has been given by Linkewich (1972).

Five resource and six tactical decisions have been considered. Assuming, for the sake of discussion, a maximum of five air tankers and five drops per air tanker, there are 36 choices available to the manager indicated in Fig. 9. Further complicating the picture, four of the drop tactic choices are themselves decision variables. If three options are assumed for each (i.e. low, medium, and high), there are 8 additional choices (twelve minus the original four), making 44 options available to the decision maker. There are nearly half a million[1] possible combinations that could be selected based on the available set of 44 choices. Clearly, selecting the optimal combination for a given fire is not a simple task. The magnitude of the problem is reduced somewhat by the fact that some decisions are not independent of others.

- Single-tanked aircraft cannot make split or sequential drops.

- Water and short-term retardants can only be used in direct attack and are poorly suited to line reinforcement.

- Independent operations preclude line reinforcement.

There remains, however, well over 100,000 possible combinations. In the real world, resource availability normally places additional limitations on the set of alternatives. For example, if only one air tanker and type of retardant were available there would be on the order of 5,000 possible combinations - still a formidable decision problem. Since this study is considering air tankers in general, the full range of combinations will be considered. During the course of model development some heuristic rules will be developed to reduce the problem to manageable proportions.

As suggested by Fig. 9 the utilization process can be subdivided into three subsystems: delivery, drop, and fire suppression. In essence, the retardant has to be moved from a storage location to the fire; it is dropped on the fire; and this results in a portion of the fire being held for some period of time. Fig. 10 indicates the relationships between the three subsystems and between the subsystems and their environments. Since the three are sequentially related, they can be discussed one at a time in the order in which they occur. This does not imply, however, that the three subsystems can be analyzed independently of one another. For example, an efficient delivery system may be suboptimal with regards to air tanker utilization, if the corresponding drop subsystem is inefficient. Thus, all three subsystems must be analyzed simultaneously to assure the attainment of a global optimum.

B. The Delivery Subsystem

The objective of the delivery subsystem is to deliver retardants to the fire in such a way that the air tanker utilization objective will be realized. This implies that obvious goals such as maximization of the quantity delivered or the rate

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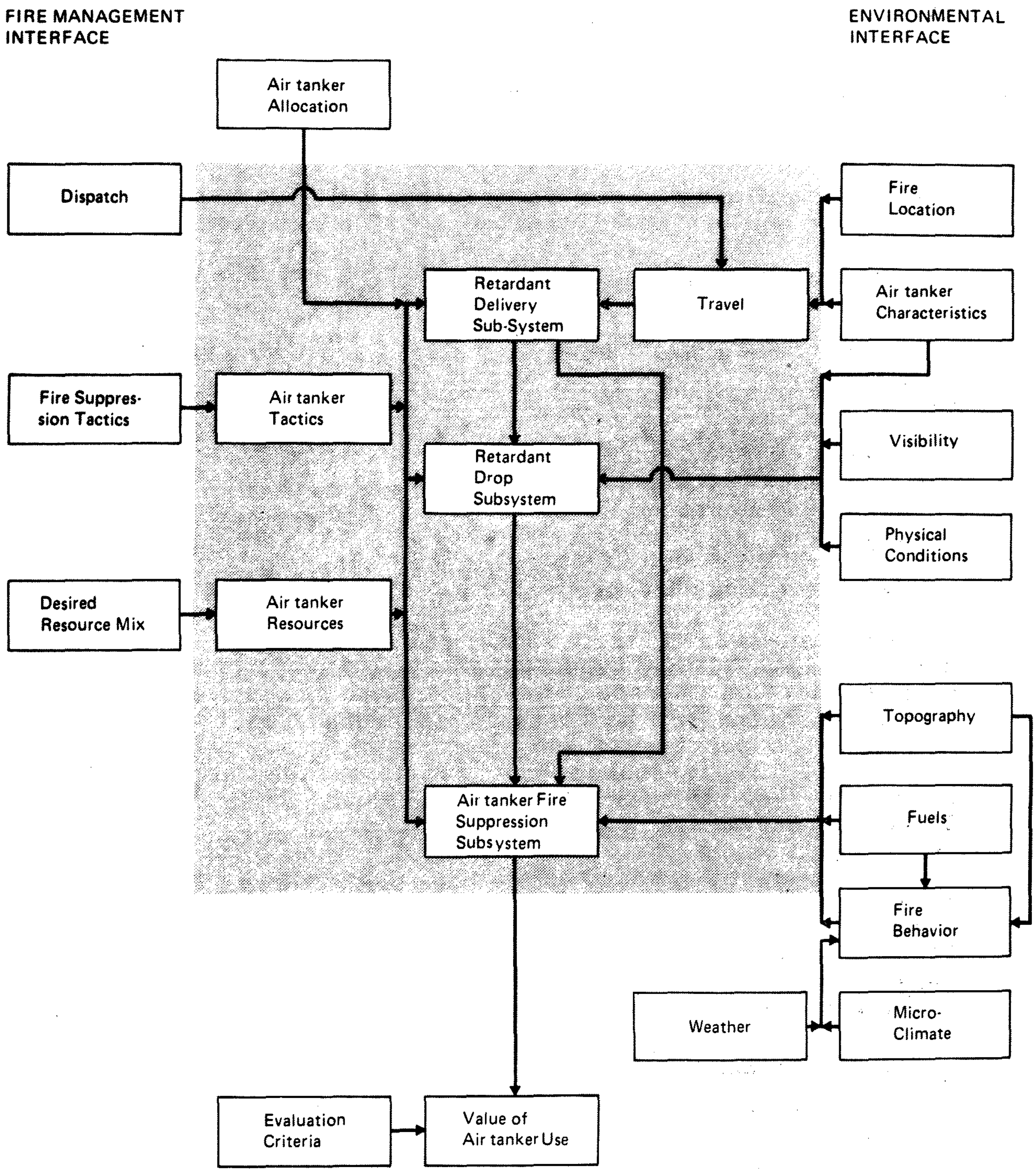
1 $1 + 5 \times 5 \times 2 \times 3 \times 3 \times 2 \times 14 \times 2 \times 2 \times 2 \times 3$.

Figure 10 Air tanker Utilization



of delivery are not necessarily superior strategies. It is noteworthy that both trends in the field towards larger and faster aircraft and a majority of previously cited studies reflect precisely these limited objectives. Quantitatively, we wish to deliver retardant to a fire such that the overall cost-plus-loss is minimized - clearly a significantly more difficult problem than simply maximizing retardant delivery.

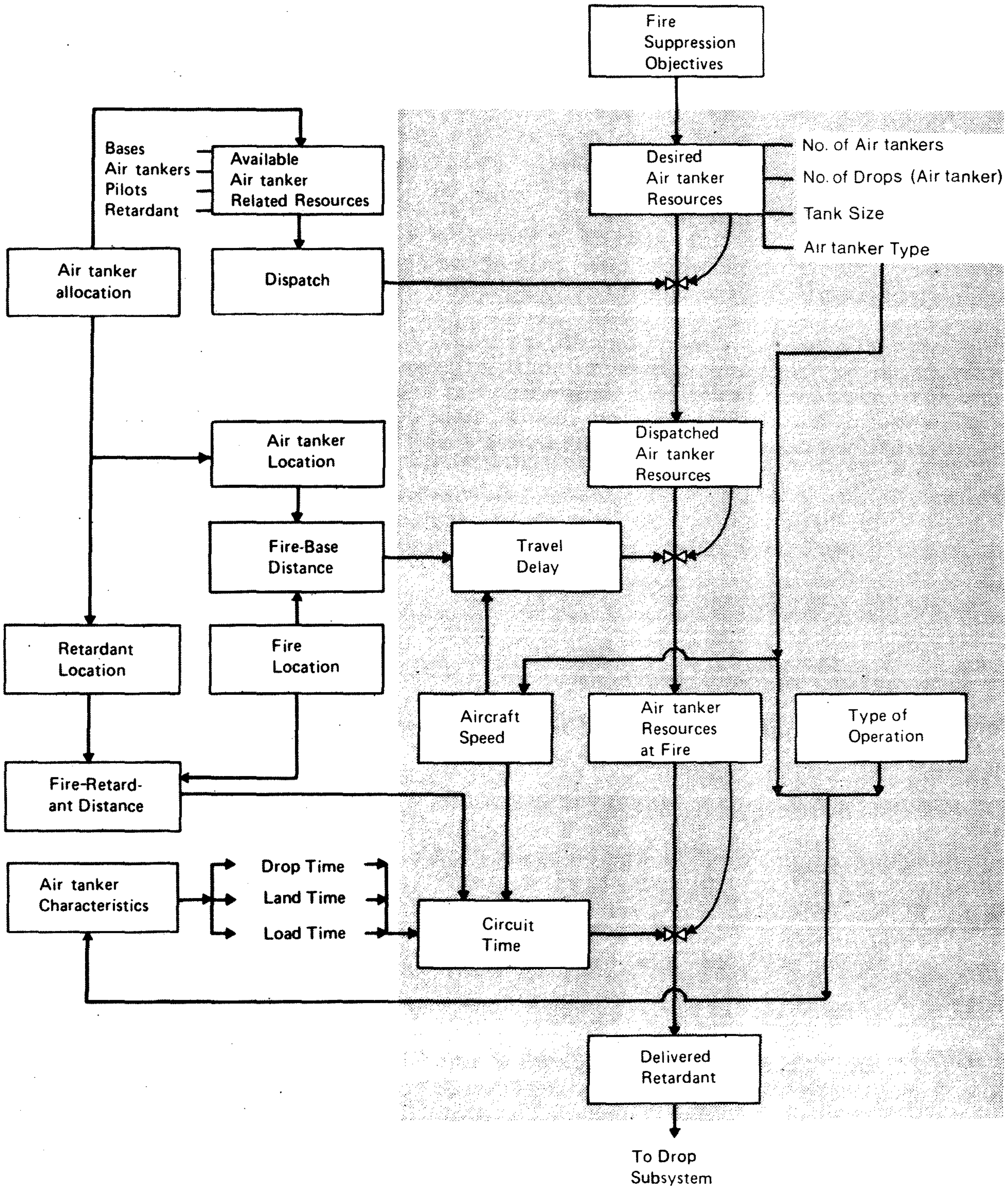
Linkewich (1972) lists two air tanker "operating concepts". In reality, the concepts describe aggregations of resources and tactics related to the delivery subsystem such that they lie at opposite ends of the operating spectrum. He refers to the "one strike concept" and the "gallons per hour concept". In the former, retardant is delivered to the fire in sufficient quantity that the entire perimeter can be held on the basis of the initial dispatch. In the latter concept, a smaller number of air tanker are dispatched with the intent that they will continue to deliver retardant until the fire is under control. Although he associates the former with land-based operations and the latter with water-based, there is no reason why both concepts could not be applied to both types of operations. Since the delivery subsystem is highly flexible, however, it stands to reason that delivery should be tailored to each individual fire rather than simply opting for an "all or nothing" approach at the outset. It is the intent of this study to proceed in the former manner.

A flow chart of the delivery subsystem is shown in Fig. 11. It is the simplest of the tnree subsystems. Retardant delivery is essentially the process of physically transporting the material from one location to another. Input and output are the same - only their location differs. Due to the lack of transformation in a physical sense, the delivery subsystem is easy to measure, understand, and model.

Air tanker allocation provides a mix of available resources. The manager selects a mix of desired resources. Operationally, it is generally the case that the desired mix forms a subset of the available mix. While the manager does not generally concern himself with the availability of pilots and retardants, the dispatcher must. The former can be highly significant as the number of allowable flying hours per time period is approached. Other resources, such as mechanics, fuel, spare parts, etc., are reflected in the availability of air tankers and are thus not of concern at this system level.

The two sets are combined and a dispatch decision is made. The air tankers arrive at the fire after a delay which is related to the fire-to-base distance and aircraft speed. Finally, after a second delay caused by circuit time, the retardant is delivered to the fire. Obviously, on the initial flight, the loading and takeoff delay occur prior to the travel delay. Circuit time is a function of the fire-to-retardant distance, the type of operation, and the characteristics of the air tanker being used. A review of the literature indicates that there are no major

Figure 11 **Delivery Subsystem Flow Chart**



studies which concerned themselves exclusively with retardant delivery. In all cases, where the delivery subsystem has been analyzed, it was incorporated with analyses of other subsystems.

C. The Drop Subsystem

The objective of the drop subsystem is to translocate the retardant from the aircraft to the ground. The retardant should be distributed on the ground in such a way that its fire suppression productivity is maximized. This transformation links the delivery and air tanker fire suppression subsystems.

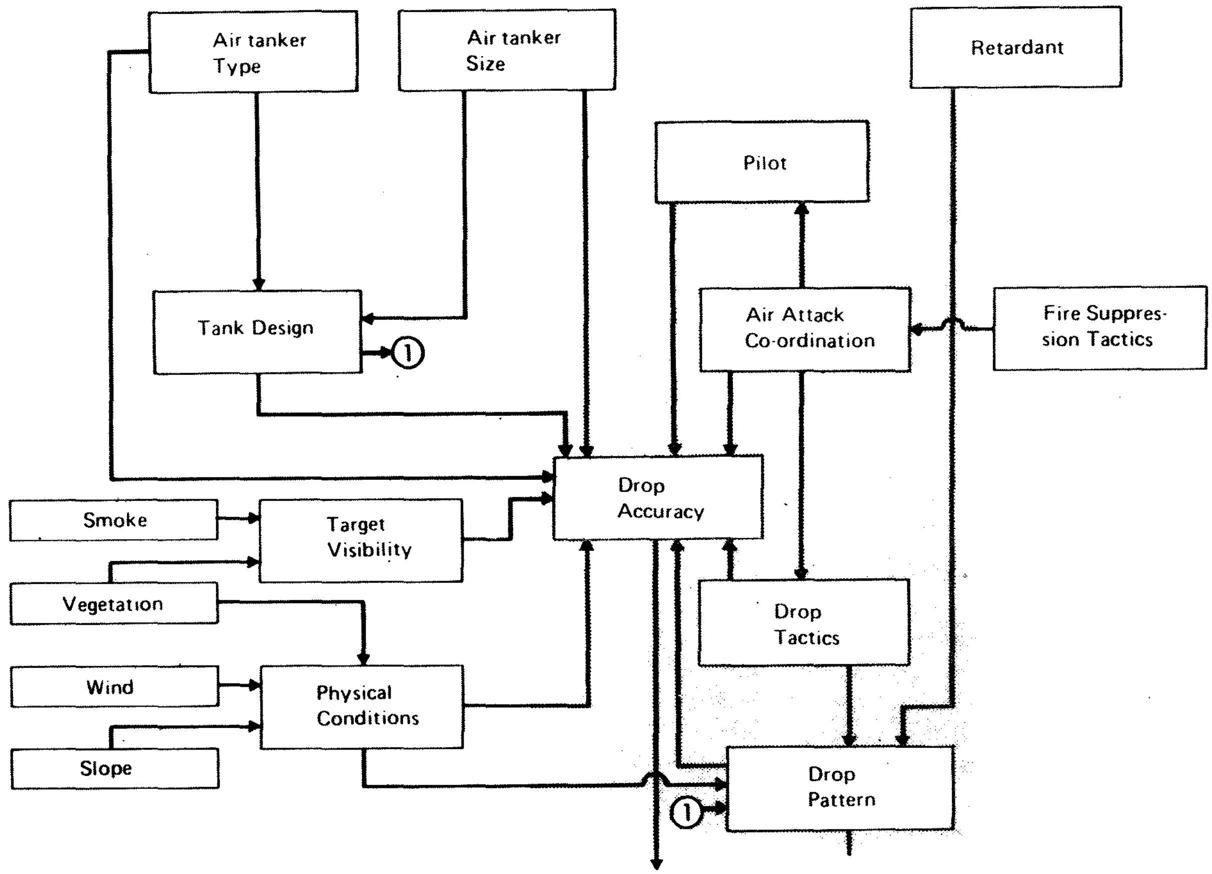
From a systems point of view, the drop subsystem is relatively simple. It simply changes the form and location of a mass of liquid. There are only two primary output components: the drop pattern (distribution of the load on the ground) and drop accuracy (the location of the pattern relative to the most effective location). On the other hand, the physical transformation process itself is extremely complex and only partially understood.

The drop subsystem is shown in Fig. 12. Fire suppression tactics control the air attack coordinator who, in turn, controls the drop subsystem by selecting drop tactics, drop location, and supervising the pilot. Drop tactics, along with retardant, physical conditions, and tank design affect the drop pattern in a complex manner. Drop accuracy is even more difficult to assess. Some of the factors which are thought to influence it are: the pilot, the air attack coordinator, drop tactics, drop pattern (in terms of area covered), physical and visibility conditions, tank design, and the type and size of air tanker.

Analysis of drop patterns has been tackled from a number of different approaches. Some workers have developed mathematical models of the drop process: MacPherson (1966), Newburger and Shanks (1966), and Swanson and Helvig (1974). Others have concentrated on the influence of tank design: Stade (1966b) and Hawkshaw (1969).

The majority of the literature, however, is concerned with empirical observations. Initial tests concentrated on obtaining drop patterns with virtually all external parameters held constant: Davis (1959), Hodgson (1967), and Elliot (1971). Gradually, more of the parameters were varied: Anderson (1971),and George and Blakeley (1973). Blakely developed regression equations to predict drop patterns for a TBM air tanker. It would appear that there is a wealth of data currently available to develop a reasonably accurate empirical model of the drop pattern component of the drop subsystem.

Figure 12 **Drop Subsystem Flow Chart**



Drop accuracy has received considerably less attention. Air tanker drop effectiveness has been discussed at length in qualitative terms particularly from the pilot's point of view by Linkewich (1972), and in more general terms by Swanson et al (1975). La Mois (1961) developed a table indicating the probability of hitting a target as a function of pattern size. Finally, Quintilio and Anderson (1975) found that only 40% to 60% of all drops hit a prearranged target.

D. The Air Tanker-Fire Suppression Subsystem

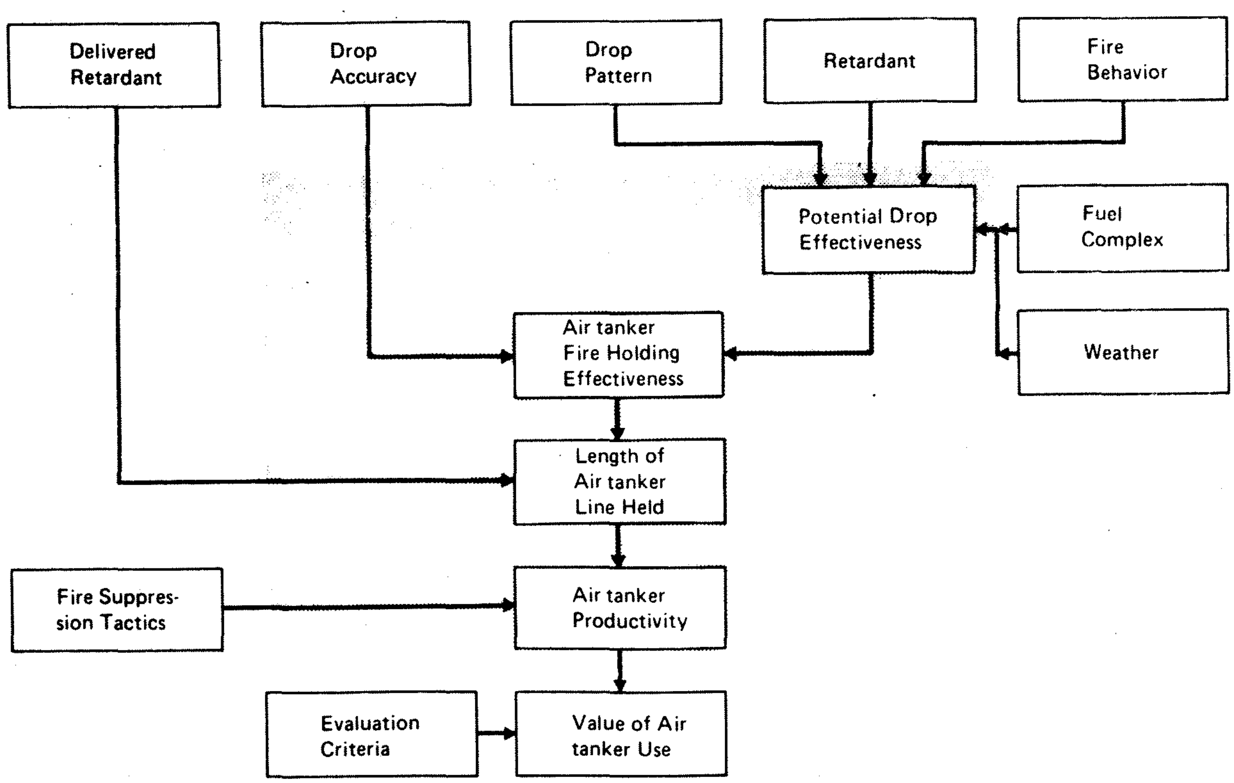
The retardant is on the ground. The air tanker has completed its mission and it is free to return to its base. The air tanker-fire suppression subsystem is clearly the key component of the air tanker system, however, in that it links the air tanker and fire control systems. Retardant on the ground is of no value per se. It has to hold the fire for some period of time. Thus, a meaningful measure of air tanker production is the length of fire perimeter held. Productivity would be the length of line held per unit of time.

As is illustrated in Fig. 13, we are again dealing with a simple flow-through system and a complex process. Potential drop effectiveness is a function of the drop pattern, retardant used, fire behavior, fuel complex, and weather. Line holding effectiveness is, in turn, a function of potential effectiveness and drop accuracy. When the quantity of retardant delivered is added, the length of fire perimeter held can be determined. Finally, air tanker productivity is determined by combining the latter with fire suppression tactics to insure that the perimeter which has been held is compatible with the overall objective.

The literature reveals that some quantitative work has been done with respect to air tanker productivity. Morgan (1969) developed a procedure to evaluate, in a relative sense, a number of air tankers currently being used in Canada. Maloney (1968) used a gaming approach in an attempt to determine the relative line holding ability of four air tanker types under a variety of environmental conditions found in California. Simard and Forester (1972) examined the costs and productivity of several fixed and rotary wing air tankers.

One final step is required in this analysis. Air tanker productivity must be related to the fire control system. This can be accomplished by determining air tanker effectiveness. Given the overall fire control objective of minimizing cost-plus-loss, the most meaningful criteria of air tanker effectiveness would be the reduction in cost-plus-loss achieved through the use

Figure 13 Air tanker - Fire Suppression Subsystem Flow Chart



of air tankers. Other criteria could be the reduction in area burned, or the reduction in control time achieved by using air tankers. This final step will insure that results obtained through an analysis of air tanker utilization will be compatible with higher fire control system levels.

6. Summary

This report examines the use of air tankers for wildland fire suppression, from a systems point of view. Since all systems exist within a hierarchy of systems, the discussion begins with the fire control environment. There are three key processes in the fire control environment: fire occurrence controls the number of fires to which the organization must respond; fire behavior (rate of spread and intensity) governs fire growth, and hence the difficulty of control; and fire control reduces the level of burning fires. Together with their related inputs, the three processes contain the essential elements of the fire control environment.

Fire control is examined from the resource management viewpoint. There are three key activities: acquisition, allocation, and utilization. Four types of resources are needed by the fire control system: fixed assets, equipment, manpower, and expendable supplies. The characteristics of the resources (expected life span, decision flexibility, unit cost, etc.) differ markedly. Thus, significantly different analytical techniques are required for analyzing different resource acquisition problems.

Resource allocation covers a broad spectrum of activities: allocation to fixed bases; interagency, long-term, and short-term transfer; and multiple and individual fire dispatch. As with resource acquisition, the characteristics of the different allocation problems differ markedly, necessitating individually tailored analytical techniques.

Resource utilization involves two distinct activities: selecting resources and tactics, and using the resources for fire control. Utilization is the foundation of the resource management hierarchy, in that most of the decisions at all levels require a knowledge of resource productivity. A measurement of productivity and effectiveness can only be made by analyzing fire suppression effectiveness.

As a fire suppression resource, air tankers can be examined in terms of the three basic functions: acquisition, allocation, and utilization. Specific examples of the four types of resources applicable to air tanker systems are: air tanker bases, air tankers, pilots, and retardant. Conceptually, air tanker allocation differs little from resource allocation, except that the considerable flexibility afforded by air tankers makes this activity far more significant than is the case with other resources.

As with resource utilization, air tanker utilization involves a selection process as well as air tanker use. The selection of air tanker resources and tactics involves eleven decisions: type of air tanker, air tanker size, number of air tankers, number of drops, type of retardant, type of operation, drop tactics, integration with ground forces, type of attack, location of attack, and type of line. With nearly half a million possible combinations available to the manager, choosing the optimal one is not a simple task.

Air tanker utilization consists of three subsystems: delivery, drop, and fire suppression. In essence, the retardant has to be moved from a storage location to the fire, it is dropped on the fire, and a portion of the fire perimeter is held for some period of time. The principle components of the delivery subsystem are the time it takes to fly to the fire and the circuit time. The drop subsystem is more complex. The retardant is released from the tank and is transformed to a drop pattern on the ground. Interposed in the process are the effects of drop accuracy, canopy interception, and retardant viscosity.

Fire suppression involves the determination of retardant effectiveness. From this, the length of line held is obtained which, in turn, yields air tanker productivity. Finally, airtanker effectiveness in a fire suppression role can be determined by applying an evaluation criteria.

The system overview begins with broad concepts in the fire control environment and ends with a fairly detailed discussion of air tanker utilization. The discussion considers all of the components which will ultimately be required to develop a comprehensive simulation model of the use of air tankers for wildland fire suppression. In a much broader sense, it also presents a detailed example of the use of systems analysis techniques for resolving a specific fire management problem. All in all, a substantial foundation has been developed, upon which a comprehensive analysis of air tanker productivity and effectiveness will be based.

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