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SYSTEM DYNAMICS AND CONVENTIONAL APPROACHES FOR MANAGING TECHNOLOGICAL SUBSTITUTION IN NATIONAL SECURITY PLANNING

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A system dynamics model is developed to detail essential combat aircraft survivability parameters and their causal relationships for the Joint Technical Coordinating Group for Aircraft Survivability of the Department of Defense. The model is comprised of five submodels: (1) Economy Submodel, (2) Budget Submodel, (3) Procurement Submodel, (4) Attrition Submodel, and (5) Survivability Submodel. The model is illustrated using aircraft carrier oriented combat scenarios which include fleet defense, counterair, interdiction. and close surface support missions for the carrier-based aircraft. Trade-off analyses are performed to determine the allocations between procurement; operations and maintenance; and research, development, test and evaluation that will generate values of aircraft inventory, availability and survivability that optimize life cycle costs and kill-to-loss ratios.

1. BACKGROUND

This year the Virginia Polytechnic Institute and State University was awarded a research grant to develop and implement a survivability management model for use by advanced program planners. The purpose of the model is to detail the essential survivability management parameters and their causal relationships throughout the life cycle of aircraft systems, and demonstrate the feasibility of obtaining a desired level of functional capability through a given approach and the connection between current needs and future returns. Specific objectives include the forecasting of macro-behavior, predicting consequences of proposed actions and failure to act, and the conducting of sensitivity analyses to establish research and data gathering priorities, as well as providing aids to communication among those concerned with survivability issues and in their understanding.

Aircraft combat survivability is defined by the United States Department of Defense as "the capability of an aircraft to avoid or withstand a man-made hostile environment without sustaining an impairment of its ability to accomplish its designated mission". From this definition, the broad scope of the concept of survivability is evident leading the JTCG to update its response to its charter requirements to include the promotion of survivability as a design discipline and the coordination of research and development results among the military services and industry, as well as within the services.

2. OVERVIEW OF THE MODEL

The survivability problem in this research has been defined as consisting of two decision-making orientations: the hierarchical and the chronological. Regarding the former, three policy levels of defense economics and national security planning are identified: (1) the quantity of resources available to the nation in general and to the defense establishment in particular; (2) the allocation of these resources within the Department of Defense both by service -- Army, Navy, Air Force and Marines -- and function -- personnel, construction, procurement, operations and maintenance, and research, development, test and evaluation; and (3) the allocation of RDT and E resources within the Joint Technical Coordinating Group for Aircraft Survivability within the DOD. Referring to the "chronological orientation", there are the identification of decision nodes throughout the combat aircraft systems life cycles -- from mission requirements to research to conceptual design to development to preliminary design to acquisition to modification to retirement, in the case of peacetime, and to attrition, in the case of wartime.

The model is comprised of five submodels: (1) Economy Submodel, (2) Budget Submodel, (3) Procurement Submodel, (4) Attrition Submodel, and (5) Survivability Submodel. In this paper these will be represented visually in the form of causal diagrams, consistent with the system dynamics methodology. Model parameters are clearly identified and the interactions

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between the parameters displayed using arrows (solid or dashed) and signs (plus or minus). Since arrows denote the direction of causality, the two basic types of parameters--constants and variables--are easily distinguished. A parameter with only arrows emanating from it is a constant. Three types of variables used in system dynamics are also apparent. Level or state variables appear at the heads of solid arrows. Rate or change variables appear at the tails of solid arrows. Other variables are auxiliary variables. The signs on solid arrows tell whether the rate adds to or subtracts from the level variable. Signs on the dashed lines tell whether the parameters at each end of the arrow vary directly or inversely.

3. THE DEFENSE ECONOMY

The Economy Submodel is depicted in Fig. E-1. It is comprised of four subsystems: Aerospace Industry, Defense Industry (other than Aerospace), Air Transportation Industry, and Non-Defense Industry (other than Air Transportation). The Economy Submodel generates the annual "Gross National Product" and "Federal Government Budget" of the U.S. It is used to project the quantity of national resources available, now and in the future. Another important function of the Economy Submodel is to account for the critical need of a national research and development policy to sustain a healthy economic and military preparedness. Basically, the model uses the parameters, "Fraction X-Industry Product to Research" and "Fraction Government Budget to X-Industry Research", to accomplish this.

4. DEFENSE MANAGEMENT

In the previous section, organized around the Economy Submodel, we considered the highest hierarchy of defense economics--the quantity of national resources available. In this section, organized around the Budget Submodel, the questions of the proportion of these resources allocated to national security and the efficiency with which these resources are so used--are addressed. The Budget Submodel is made up of three subsystems: (1) the Procurement Subsystem, (2) the Operations and Maintenance Subsystem and (3) the Research, Development, Test and Evaluation Subsystem. The Procurement Subsystem of the Defense Budget Submodel is shown in Fig. DB-1A. Problems within the scope of these three subsystems consist in choosing efficiently, or economically, among the alternative methods of achieving military tasks, objectives, or missions. These alternative methods may be different strategies, different tactics, various forces, or different weapons.

5. PROCUREMENT

The Procurement Submodel is comprised of three subsystems: (1) Army Combat Aircraft, (2) Air Force Combat Aircraft, and (3) Navy Combat Aircraft. The portion of the Procurement Submodel dealing with the third subsystem--Navy Combat Aircraft-- is shown in Fig. P-1. Basically the inventory of each of the eight Navy aircraft shown is increased by acquisition of new aircraft or modification of an older version of the same type aircraft. Older version inventories are reduced by retirement and modification to improved versions. Both the acquisition and modifications rates depend directly on the acquisition and modification budgets and inversely with acquisition and modification costs. The acquisition and modification budgets are determined from the outputs of the Budget Submodel.

6. ATTRITION

The Attrition Submodel acts on the inventory of "Combat Aircraft" in the event of war. The number of combat aircraft increased by the outputs of the Procurement Submodel over years of peacetime are reduced in wartime through the "Attrition Rate for Combat Aircraft", which depends on the number of "Combat Aircraft"; the "Sortie Rate for Combat Aircraft", "Mission Survivability for Combat Aircraft", and the "Availability of Combat Aircraft". The Attrition Submodel is made up of ten subsystems: (1) U.S. Army Aircraft, (2) U.S. Air Force Aircraft, (3) U.S. Navy Aircraft, (4) Soviet Aircraft, (5) U.S. Air-to-Air Weapons, (6) U.S. Air-to-Surface Weapons, (7) U.S. Surface-to-Air Weapons, (8) Soviet Air-to-Air Weapons, (9) Soviet Surface-to-Air Weapons, and (10) Soviet Air-to-Surface Weapons. Fig. A-1A depicts the U.S. Navy Aircraft Subsystem and the Soviet Surface-to-Air threats it would likely face (Subsystems 3 and 9 as identified in the previous sentence).

7. SURVIVABILITY SUBMODEL

The Survivability Submodel is comprised of four subsystems: (1) Detection Susceptibility, (2) Hit Susceptibility, (3) Vulnerability and (4) Availability. The Survivability Submodel outputs are the "Mission Survivability for Combat Aircraft" and the "Availability of Combat Aircraft". The former is the product of the "Susceptibility of Combat Aircraft" and "Vulnerability of Combat Aircraft", both of which depend on the magnitude of the "Aircraft Survivability RDT&E Budget" outputed from the Budget Submodel. Reductions in the "Susceptibility of Combat Aircraft" and "Vulnerability of Combat Aircraft" affect the "Acquisition Cost of Combat Aircraft" and "Modification Cost of Combat Aircraft" used in the Procurement Submodel.

8. APPLICATION TO NAVAL AIR POWER

The concepts of tactical air power, in general, and aircraft survivability, in particular are both contingent on, and shapers of, the objectives of contemporary U.S. doctrine and what sorts of aircraft are needed for these purposes. Unlike the strategic forces, U.S. tactical forces are charged with carrying out a variety of activities aimed for the most part at defeating the enemy on the battlefield. Because the logic of technological substitution decisions with respect to specific weapon systems is based on the priority given various missions, it seems appropriate to mention the principal tactical mission areas: (1) counterair or air superiority, (2) interdiction, (3) close ground support, (4) reconnaissance and electronic warfare, and (5) tactical airlift. In the case of naval air power, these manifest themselves slightly differently; however, this example has been chosen for the sake of relative simplicity in illustrating the model.

U.S. naval air power is carrier-oriented in contrast to Soviet naval air power which, at least for the present, is still principally land-based. Probably the single most distinguishing characteristic of U.S. tactical air structure is the extent of reliance on aircraft carriers. The U.S. Navy currently operates 14 aircraft carriers (one of which is always in overhaul) consisting of 12 ships of post-World War II construction including four nuclear powered carriers. Current plans call for no increase in this number through the century, although by the year 2000, half of the 14 are expected to be nuclear powered. The rest of the world has a combined total of only nine (including four Soviet carriers), most of which are less than half the size of the typical U.S. aircraft carrier. Based on their size and design, carriers such as those possessed by the U.S.S.R. would be used for operating V/STOL aircraft against surface ships rather than projecting air power ashore--the primary role of U.S. carriers.

U.S. Naval Aviation operates more aircraft than any other country except the U.S.S.R. and China. A typical carrier air wing consists of 24 Fighter Aircraft (F-4 or F-14), 36 Attack Aircraft (A-4, A-6 or A-7), 4 Tactical Electronic Warfare Aircraft (EA-6B's), 4 Airborne Early Warning Aircraft (E-2's), 16 Antisubmarine Aircraft (S-3 and SH-3), and about 9 miscellaneous types such as reconnaissance, photographic, communications, patrol, mine countermeasures and logistic support aircraft. Since it is the Fighters and Attack Aircraft that take the war ashore, these are singled out for inclusion in the model and for discussion in this paper. Referring to Fig. P-1, computer plots for the generation of inventories of five naval fighter/attack aircraft types are shown--the A-6, A-4, F-14, F-18 and AV-8.

9. MISSION SCENARIOS

The relative mix of carrier-based fighters and attack aircraft, and how U.S. tactical air resources should be distributed between the two, centers on the survivability of the carrier. For example, the second largest tactical air program for the 1970's, the F-14, has been justified by the Navy primarily on the ground that it will improve the chances of carrier survival against a sophisticated air attack. To act as an equalizer against the American advantage of the aircraft carrier, the Russians developed Mach 2 attack-bombers capable of launching cruise air-to-surface missiles with a long-range stand-off capability. Since these missiles have a range of over 200 miles, the carrier's radar may not be able to pick up the launching bomber placing the protection of the carrier from this threat clearly on the fleet defense role of the aircraft carrier's fighters. However, the ability to counter the bomber threat is not enough. Once the cruise missiles have been launched, an effective method of dealing with these anti-ship missiles must exist. A number of the F-14's high technology features allow it to engage up to six targets in rapid sequence and at very long ranges, making it possible for this fighter to defeat both the bomber and the missile.

In addition to the fleet defense or interceptor mission of carrier-based fighters, like all fighters they must meet the counterair mission challenge. The obvious threat in a tactical situation is the enemy's fighter. Control of the air as a dominant factor in successful warfare is no longer questioned. The Russians have learned this historical lesson and have been pursuing the development of first class fighters like the MIG-21 and MIG-23. These are two current threat aircraft that modern U.S. carrier-based fighters such as the F-14 and F-18 are designed to counter so as to fulfill their air superiority mission.

Tactical airpower can be divided into two groups: planes that fight other airplanes as discussed above and those that attack surface targets. Each group can be further divided into components according to range and weight (or size). The mission in which planes fly across the front line of battle or, in case of carrier-based aircraft, penetrate inland to attack targets such as bases, airfields, roads, pipelines, depots, etc., at long range is called interdiction. In contrast to the long distance typical of interdiction, close air support aircraft attack nearby surface targets including enemy ships. For example, the A-4 was developed in the 1950's as a lightweight, daylight only nuclear strike aircraft for use in large numbers from aircraft carriers. In contrast, the A-6 is an all-weather and night attack aircraft developed for conventional surface attack. Then there is the AV-8B to be flown in the light attack role by carrier-based marine squadrons in support of landings. In short, U.S. carrier-based attack aircraft fulfill the same functions as Soviet land-based naval strike-bombers described in this section.

In Fig. CS-13 a causal diagram for the portion of the JTCG/AS Model used to generate carrier-based mission scenarios is shown. The submodel shown consists of three components: (1) an attrition component (approximately the top half of the diagram); (2) a peacetime-buildup component (essentially the bottom 40% of the diagram below the parameter KLR, Kill to Loss Ratio; and (3) a trade-off component (across the middle of the page). The two principal generic types of U.S. carrier-based aircraft, fighters and attack aircraft, are designated $F and $A. Their Soviet counterparts are XF and XA. Using this submodel, survivability, availability, and inventory tradeoffs can be performed for navy combat aircraft as will be explained in the next section.

10. TRADE-OFF ANALYSIS

One of the great ironies of the civil efficiency/military effectivenesses mismatch is the contradictory ways in which new technology is viewed in different environments. Applied in industry it is referred to as progress; employed in the military it is called "gold plating". American defense planners have long assumed, properly, that U.S. weaponry must be technologically superior to the Soviet Union's. Spending on technology makes sense in our military, just as in the private sector, because it is typically a substitute for people, and in our society people is a more valuable resource than capital. Some economy-minded defense reformers have failed to see the weapons-evolution phenomenon for what it really is--the same technological substitution trend that is taking place across society.

Waging war is no different in principle from any resource transformation process, and improvements should be pursued just as vigorously as for farming, mining, manufacturing and construction. If anything, automation within the military makes even more sense than in other sectors where human labor is consumed only figuratively.

The ultimate technological assessment for combat aircraft is the level of attrition, or loss of mission capability under combat conditions. If attrition is higher than expected and mission objectives cannot be fulfilled due to misguided peacetime preparations, it is too late to do anything about it after war starts. The measures of mission effectiveness are varied so that any system can be evaluated with respect to its mission objectives. The two measures used in this trade-off analysis are "Life Cycle Cost per Surviving Aircraft" and "Kill-to-Loss Ratio". Basically, the problem can be stated as follow: allocate a given "Program Cost of Combat Aircraft" between procurement, operations and maintenance (O&M), and research, development, test and evaluation (RDT&E) so as to obtain the combination of aircraft inventory, aircraft availability, and aircraft survivability that will optimize the measure of effectiveness selected.

Table 1 presents a summary of how a trade-off analysis would be performed for a special case of the model shown in Fig. CS-13 in which, instead of two distinct aircraft $F and $A, a multi-mission aircraft designated $F/A is utilized. Such an aircraft actually exists in the form of the F/A-18 since McDonnell Douglas has developed the attack version of the F-18. Moreover, for the past decade the Navy has studied the possibility of a multi-mission VTOL referred to as the VFMX.

II. MODELING TECHNOLOGICAL DEVELOPMENT

The technological development process, as applied to combat aircraft, can be thought of as a series of prototype problems that tend to emerge throughout the life cycle of the aircraft system. Basically these can be reduced to the acquisition, distribution, allocation, utilization and scheduling of resources. A number of techniques of operations research, management science, and systems analysis have evolved which lend themselves to modeling the individual prototype problems such as input-output analysis, inventory theory, queueing theory, linear programming, PERT, etc. A few of these (see figure) have been utilized in this research in conjunction with system dynamics, and will be discussed briefly.

The input-output method depicts the structure of an economy in terms of the flows among its producing and consuming sectors. Such transfers are displayed in an "input-output table" for an economy. In the figure the U.S. economy has been depicted in terms of two sectors, Basic (for Defense Industry) and Non-Basic (for Non-Defense Industry) so as to facilitate showing the relationship between input-output and system dynamics modeling. In the model four sectors are used as shown in Fig. E-1. The input-output framework provides a point-of-departure in determining the impact of a defense buildup on the whole economy and the impact of investment in R&D by industry and/or government on military strength.

Military decisions may be classified by kind as well as by level. It is useful to distinguish: operations decisions (strategy and tactics), procurement or force composition decisions, and research and development decisions. The basic difference among these kinds of decisions, from the point of view of analysis, is the time at which the decision affects the capability of the military forces concerned. An operations decision can affect capability almost immediately. A decision to procure something, on the other hand, cannot affect capability until the thing procured has been produced and fitted into operational forces. Finally, decisions to develop something based on researching it tend to affect capabilities at an even later date--after the system has been developed, procured and fitted into operational forces. Inventory theory (see figure) provides the conceptual device for trading-off force size and force availability through the allocation of financial resources between procurement and operations and maintenance.

The basic mission trade-off model depicted in Fig. CS-13 has two end products. The first is the determination of the force composition of aircraft to accomplish the set of mission objectives in the combat scenario. The second is to accomplish these objectives as minimum cost. The latter is addressed in Table 1 using a single multi-mission aircraft. Suppose, however, we return to the more conventional situation in which two types of carrier-based aircraft are used, $F and $A. The numbers of each required to do their respective jobs are plotted in the figure, "Linear Programming" as constraints on the graph. The third constraint is the aircraft carrier capacity (for accommodating these two types of aircraft). The solution space determined by these three constraints is shown on the graph. If the objective function is total program costs of the two, one can easily superimpose these on the graph to determine the optimum number of each type of aircraft.

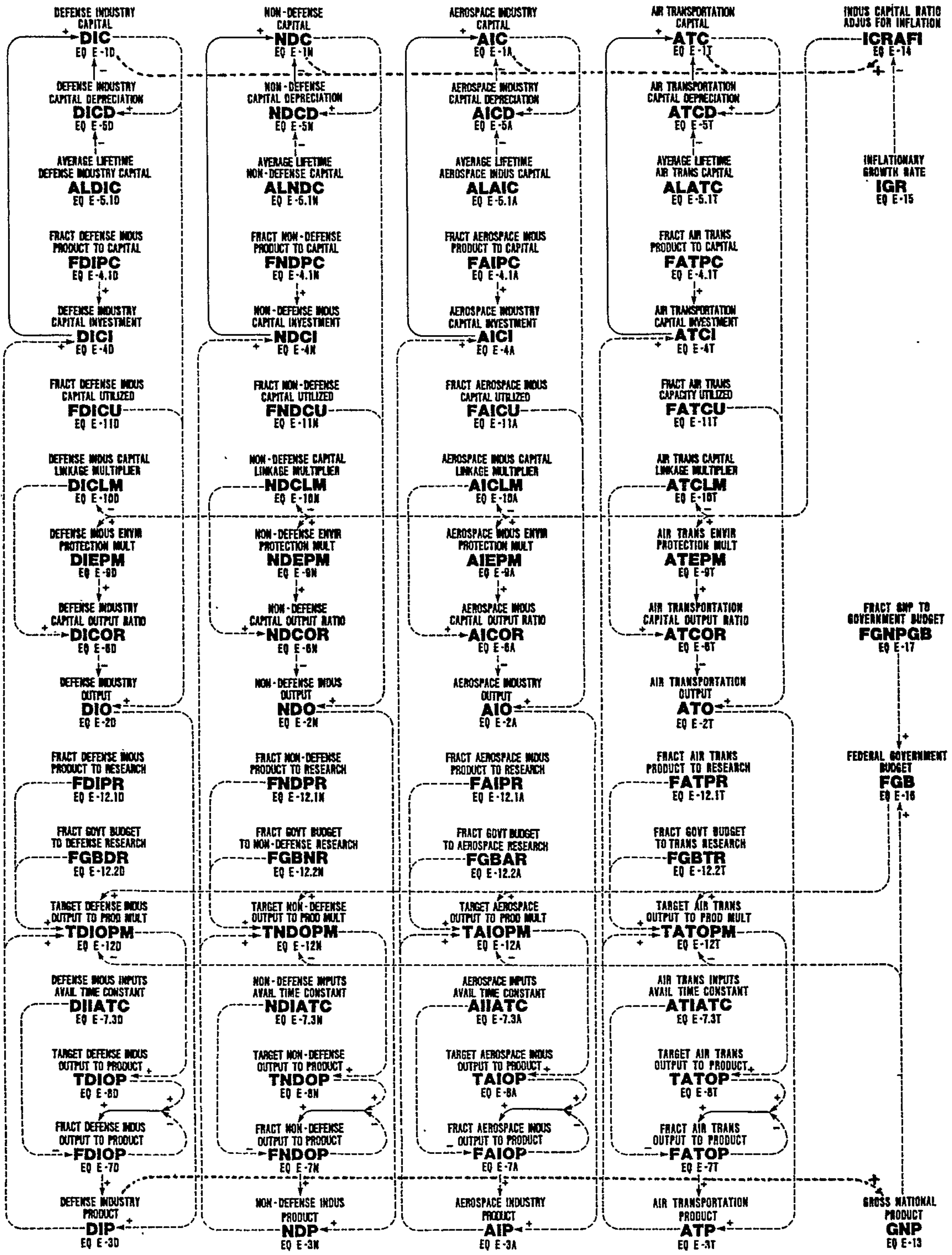


FIG E-1 ECONOMY SUBMODEL

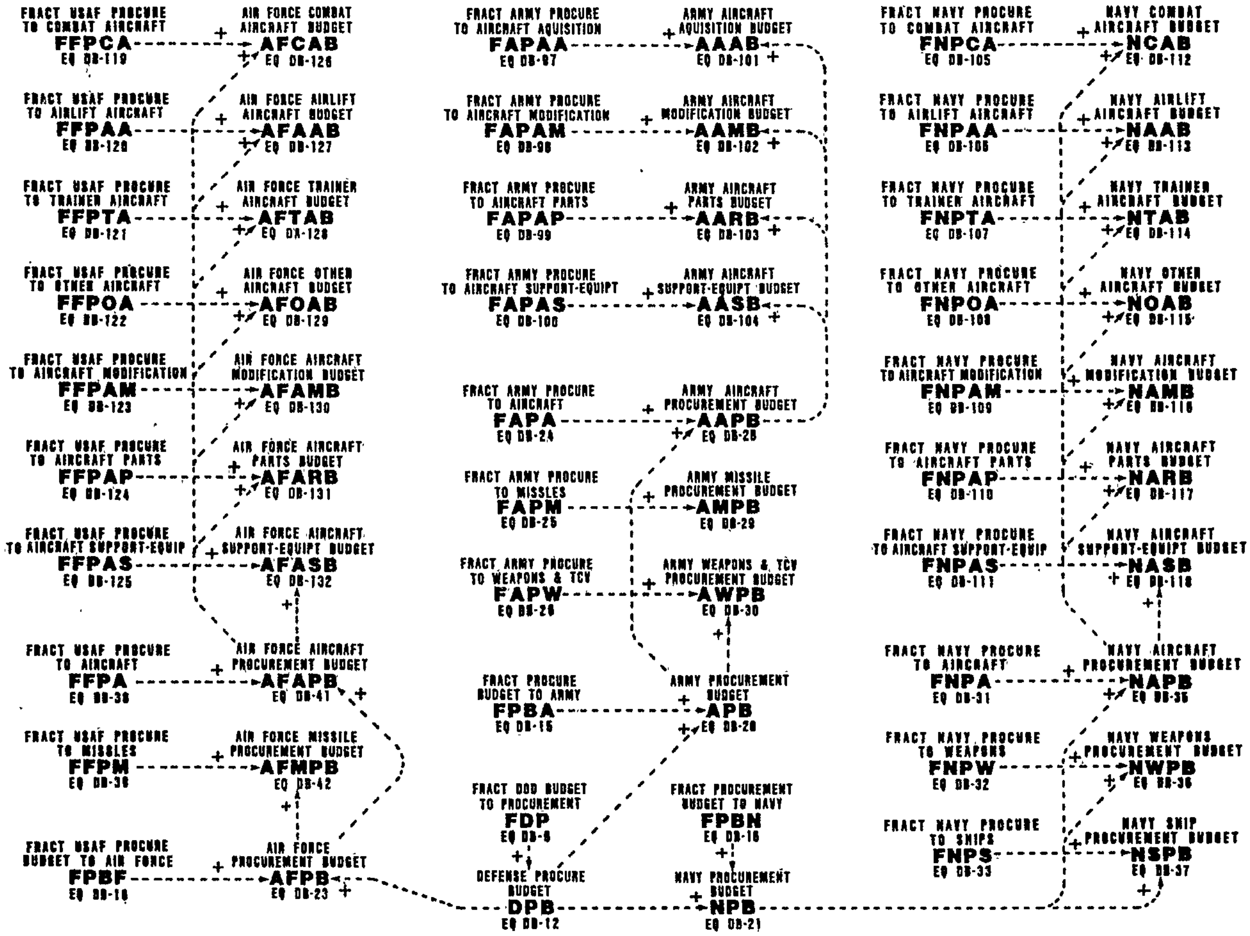


FIG DB-1A DEFENSE BUDGET SUBMODEL

TABLE 1

FDOM	FDP	FNRCA	AV$F	$F	MS$F	FC$FOM	FC$FP	FC$FRD	PC$F	UPC$F	AC$F	LCC$F	KLR
.25	.35	.05	.2957	1014	.900	.3584	.6211	.020	76.55B	75.47M	53.81M	103.4M	2.368
.30	.30	.05	.4140	869	.900	.4376	.5416	.021	75.24B	86.55M	53.81M	117.9M	2.786
.35	.25	.05	.5398	724	.900	.5195	.4593	.021	73.94B	102.10M	53.81M	145.8M	2.956
.25	.35	.10	.3726	804	.950	.3512	.6086	.040	78.11B	97.04M	67.80M	134.1M	2.885
.30	.30	.10	.5108	690	.950	.4286	.5305	.041	76.81B	111.30M	67.80M	154.4M	3.348
.35	.25	.10	.6152	575	.950	.5087	.4498	.042	75.50B	131.30M	67.80M	199.0M	3.278
.25	.35	.25	.5029	593	.980	.3313	.5741	.095	82.82B	139.60M	92.02M	209.1M	3.267
.30	.30	.25	.6063	508	.980	.4039	.4999	.096	81.51B	160.30M	92.02M	260.6M	3.281
.35	.25	.25	.7456	423	.980	.4789	.4234	.098	80.21B	189.30M	92.02M	353.3M	3.253
.25	.35	.50	.5679	471	.990	.3026	.5244	.173	90.66B	192.20M	115.70M	357.0M	2.946
.30	.30	.50	.6951	404	.990	.3685	.4561	.175	89.35B	221.00M	115.70M	469.6M	2.981
.35	.25	.50	.8116	337	.990	.4362	.3857	.178	88.05B	261.30M	115.7M	941.0M	2.604

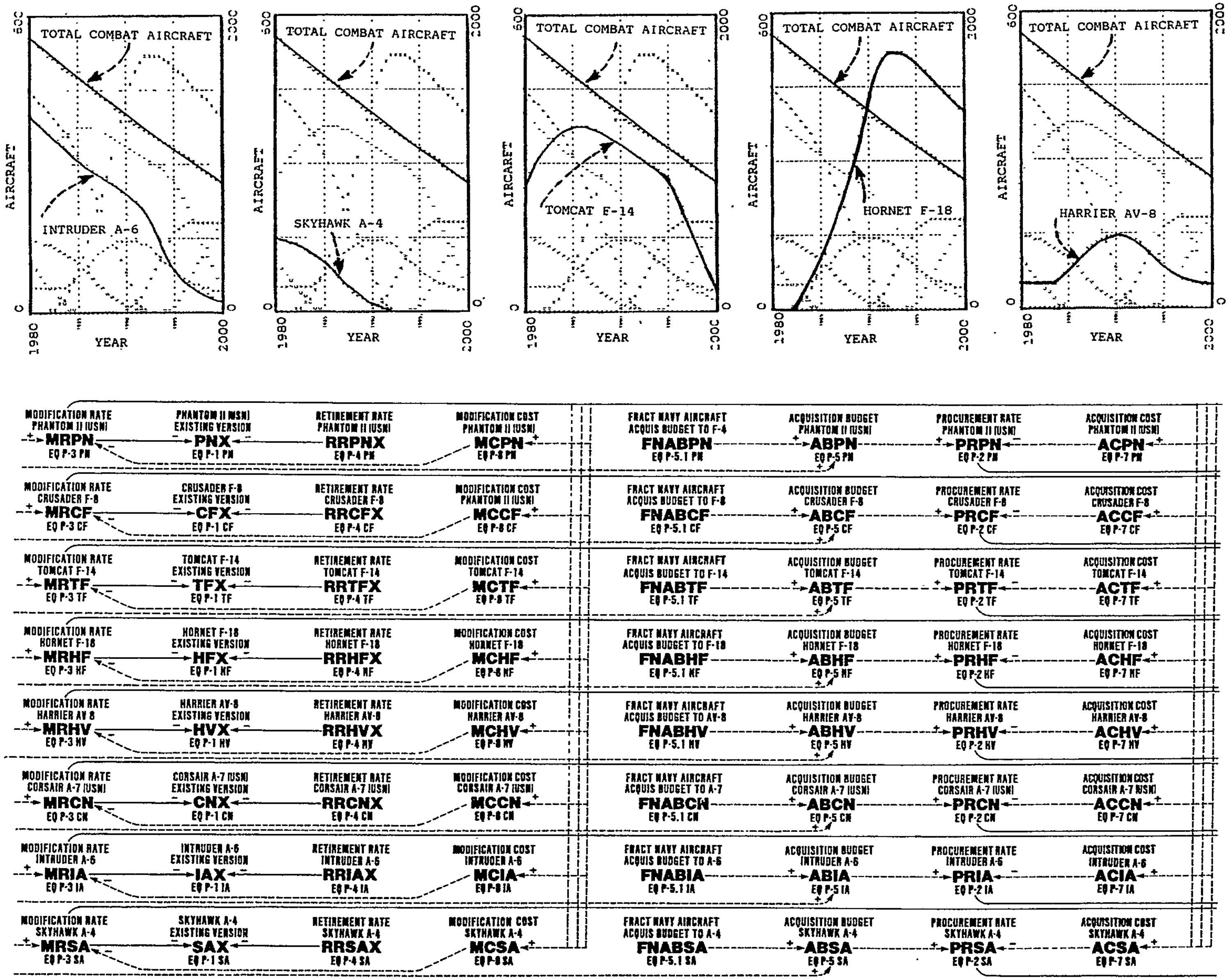


FIG P-1 PROCUREMENT SUBMODEL

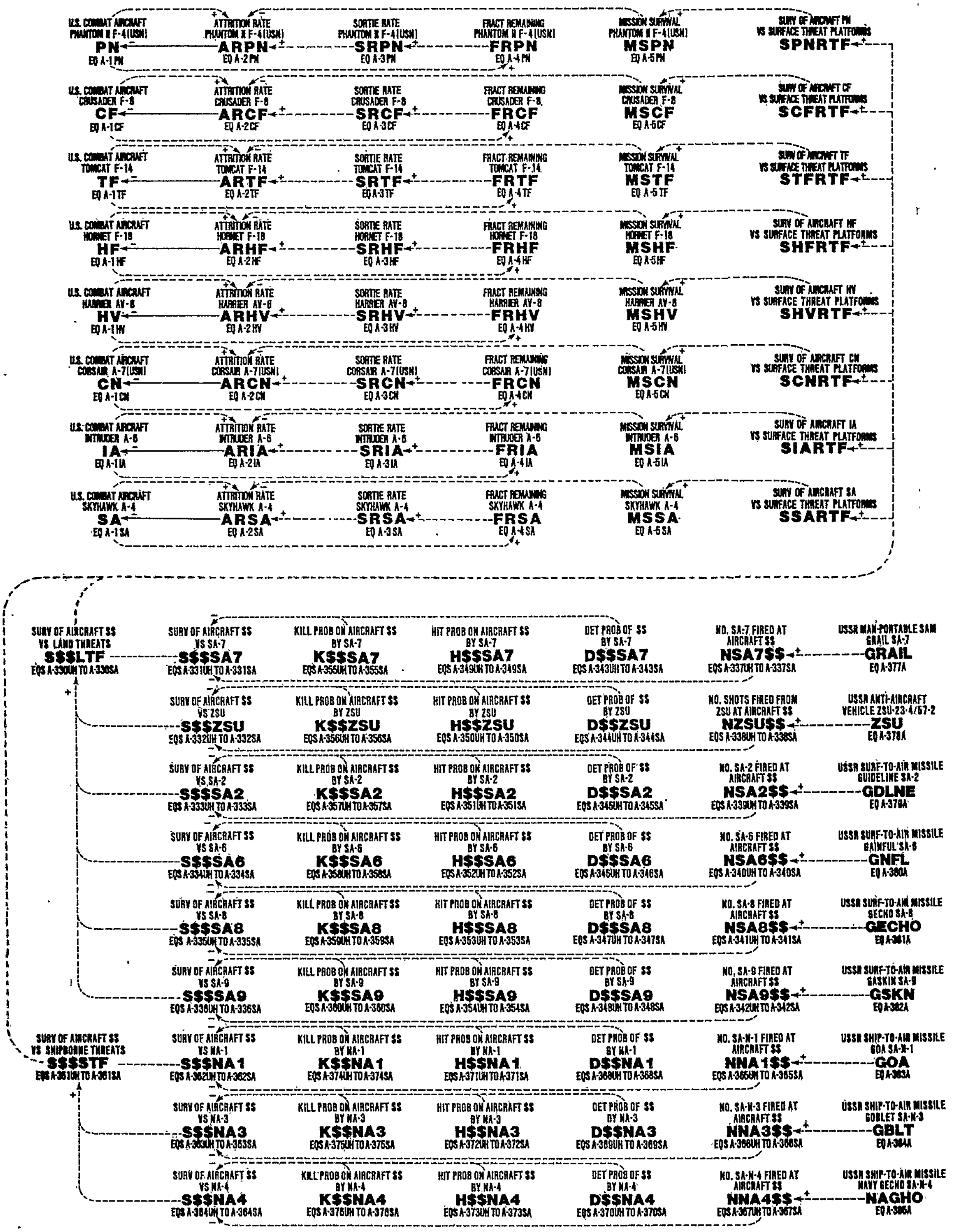


FIG A-1A ATTRITION SUBMODEL

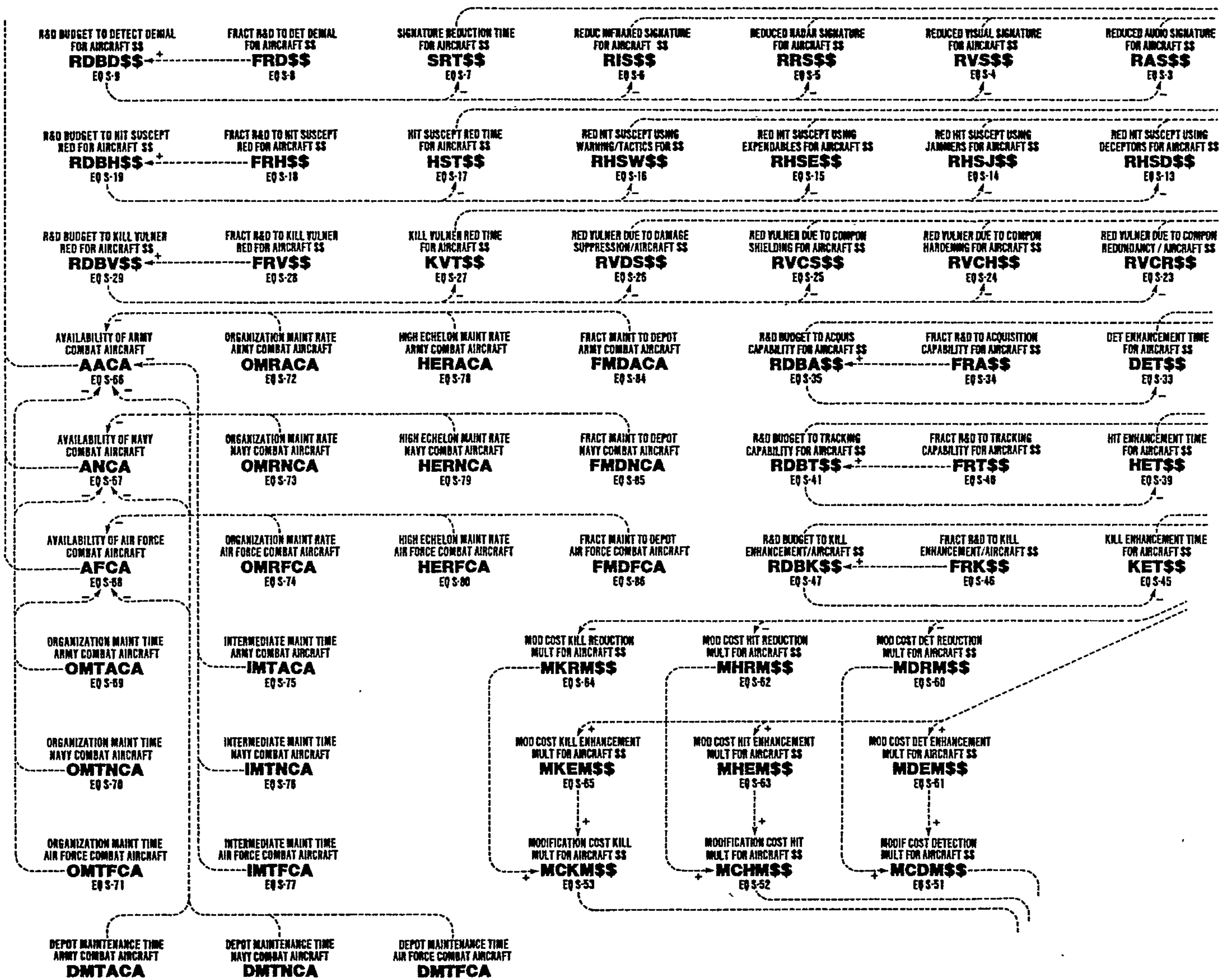
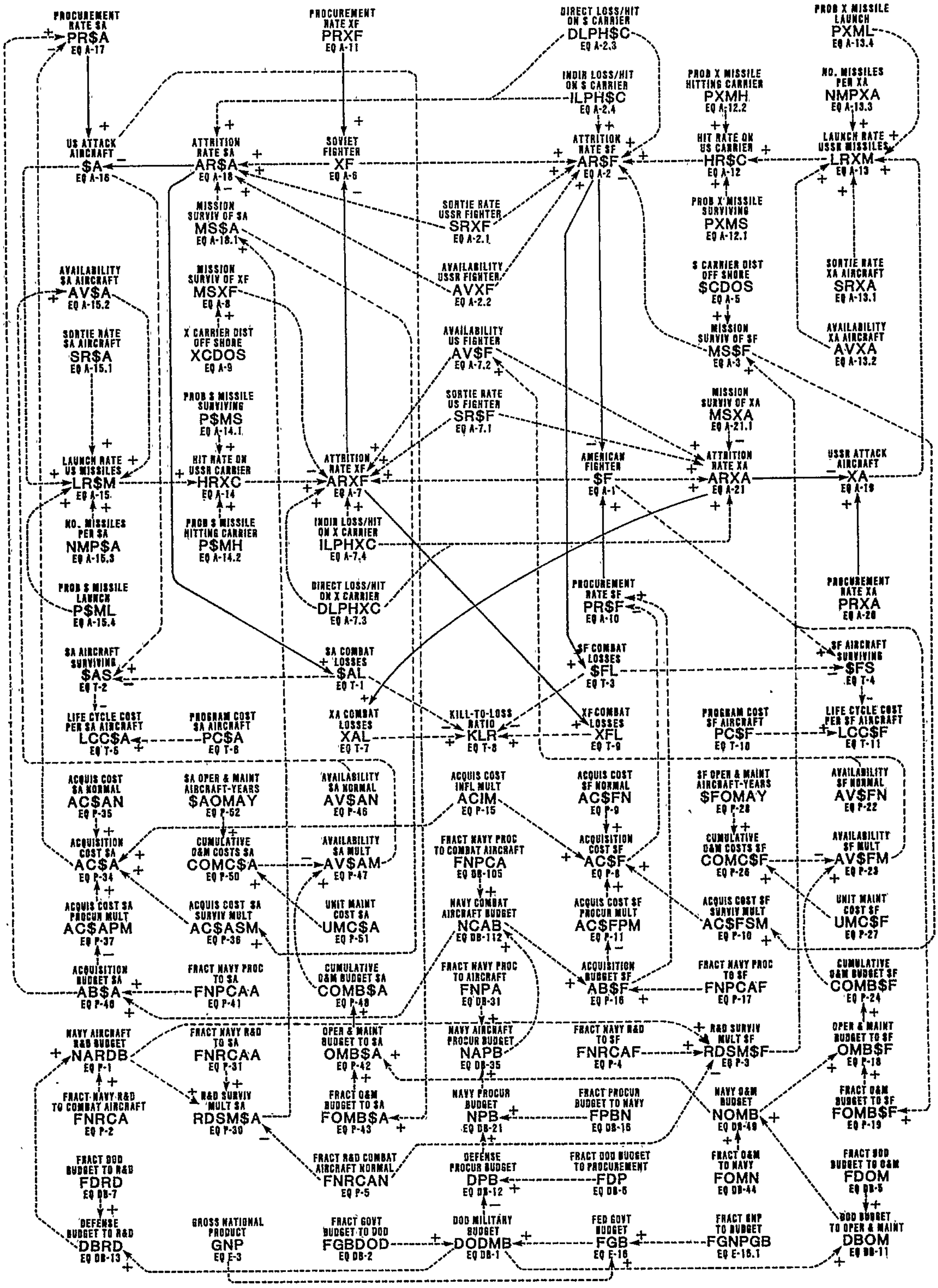


FIG S-1B SURVIVABILITY SUBMODEL



SURVIVABILITY,AVAILABILITY,INVENTORY TRADE OFFS FOR NAVY COMBAT AIRCRAFT

FIG CS -13

INPUT-OUTPUT EQUATION

$$\begin{bmatrix}\text{BO}\\ \text{NO}\end{bmatrix}-\begin{bmatrix}\text{FBB}&\text{FBN}\\ \text{FNB}&\text{FNN}\end{bmatrix}\cdot\begin{bmatrix}\text{BO}\\ \text{NO}\end{bmatrix}=\begin{bmatrix}\text{BP}\\ \text{NP}\end{bmatrix}$$

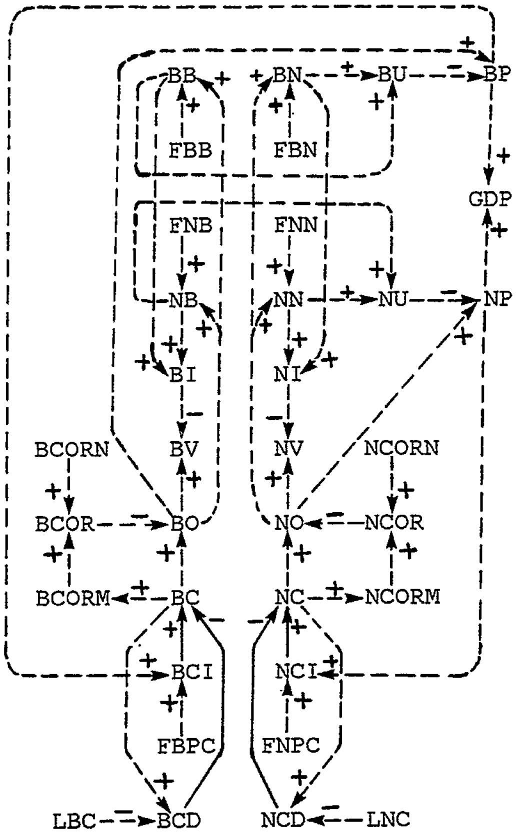
WHERE FBB=BB/BO FBN=BN/NO
FNB=NB/BO FNN=NN/NO

BC-BASIC SECTOR CAPITAL
BCI-BASIC SECT CAP INVESTMENT
BP-BASIC SECTOR PRODUCT
FBPC-FRACT BASIC PROD TO CAPITAL
BCD-BASIC SECT CAP DEPRECIATION
LBC-LIFETIME BASIC SECT CAPITAL
BO-BASIC SECTOR OUTPUT
BCOR-BASIC SECT CAP OUTPUT RATIO
BCORN-BASIC CAP OUTPUT RATIO NORM
BCORM-BASIC CAP OUTPUT RATIO MULT
BI-BASIC INPUTS
FBB-FRACT BASIC INPUT FROM BASIC
FNB-FRACT BAS INPUT FROM NON-BAS
BV-BASIC VALUE-ADDED
BU-BASIC USAGE
BB-BASIC INPUT FROM BASIC
BN-BASIC INPUT FROM NON-BASIC
NC-NON BASIC SECTOR CAPITAL
NCI-NON BASIC SECT CAP INVESTMENT
NP-NON BASIC SECTOR PRODUCT
FNPC-FRACT NON BASIC PROD TO CAP
NCD-NON BASIC CAP DEPRECIATION
LNC-LIFETIME NON BASIC SECT CAPITAL
NO-NON BASIC SECTOR OUTPUT
NCOR-NON BAS SECT CAP OUTPUT RATIO
NCORN-NON BAS CAP OUTPUT RAT NORM
NCORM-NON BAS CAP OUTPUT RAT MULT
NI-NON BASIC INPUTS
FNN-FRAC NON BAS INPUT FROM NON BAS
FBN-FRACT NON BAS INPUT FROM BASIC
NV-NON BASIC VALUE-ADDED
NU-NON BASIC USAGE
NN-NON BASIC INPUT FRON NON BASIC
NB-NON BASIC INPUT FROM BASIC

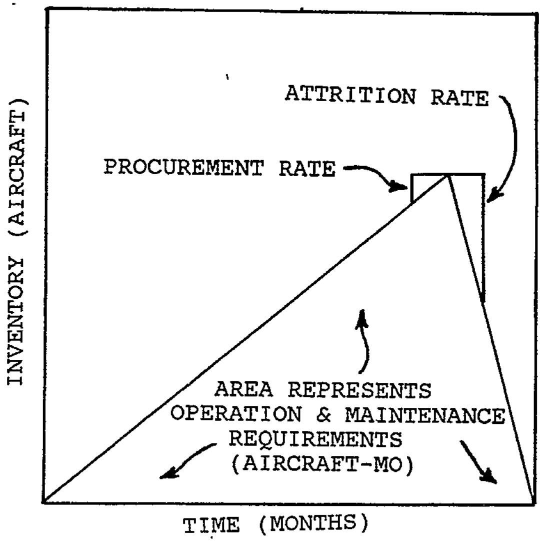
INPUT-OUTPUT TABLE

	B	N			
B	BB	BN	BU	BP	BO
N	NB	NN	NU	NP	NO
	BI	NI			
	BV	NV			
	BO	NO			

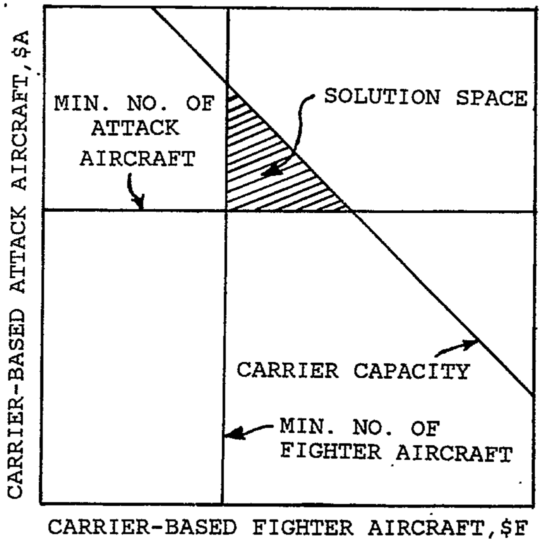
CAUSAL DIAGRAM



INPUT-OUTPUT ANALYSIS



INVENTORY THEORY



LINEAR PROGRAMMING