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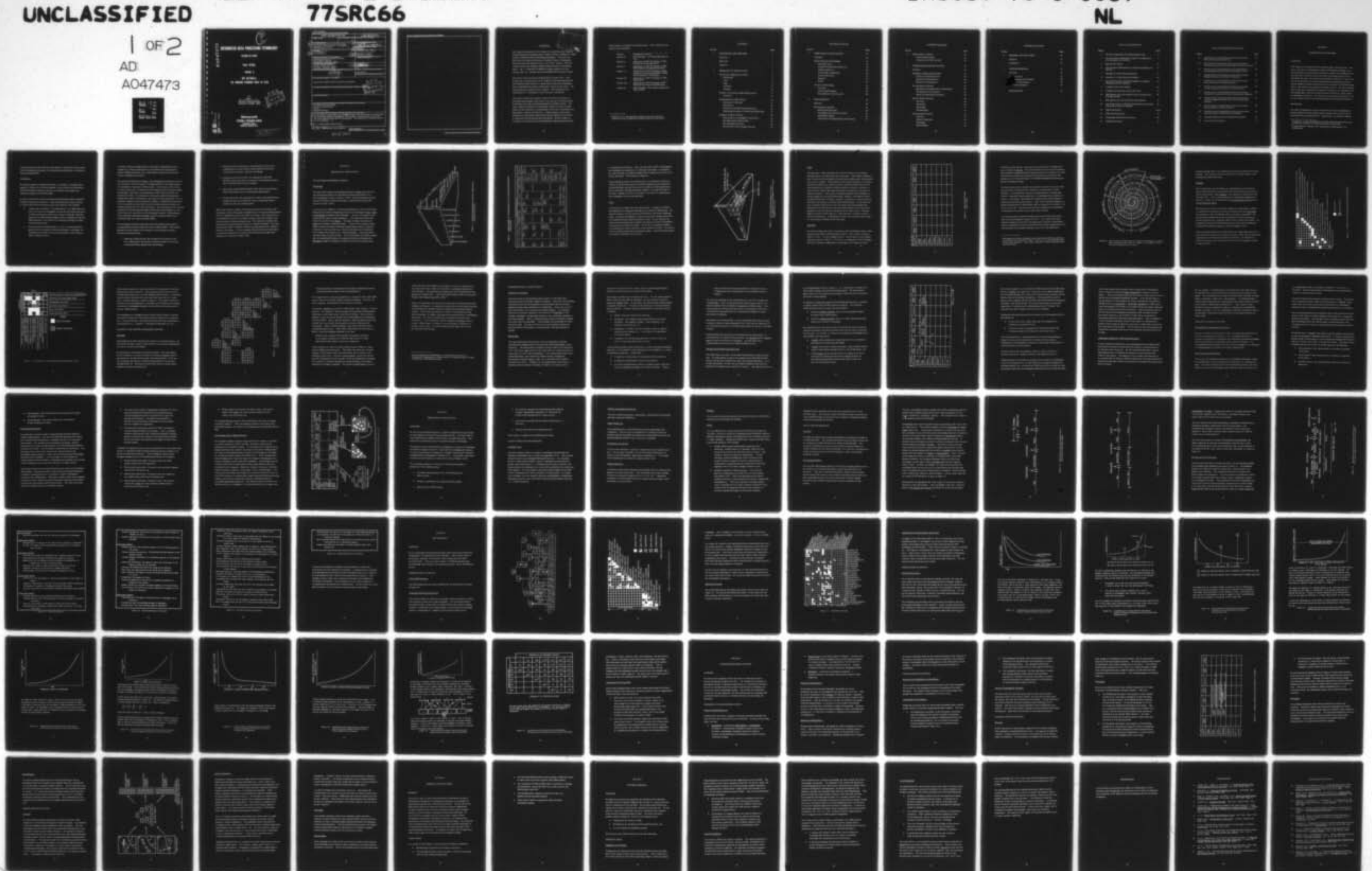

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DISTRIBUTED DATA PROCESSING TECHNOLOGY

DASG60-76-C-0087

FINAL REPORT

VOLUME II

DDP RATIONALE:
THE PROGRAM PLANNING POINT OF VIEW

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DEC 8 1977
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For
BMDATC
Ballistic Missile Defense
Advanced Technology Center
Huntsville, Alabama 35807

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The possibility of quantifying the payoffs* associated with the application of distributed data processing (DDP) is investigated. The problem of quantification is discussed and a set of non-quantified payoffs is presented. Two approaches to quantified payoffs are also developed.

*i.e., nonfunctional requirements

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FOREWORD

The research documented in this volume was conducted under Ballistic Missile Advanced Technology Center contract number DASG60-76-C-0087, entitled "Distributed Data Processing Technology." This work was performed by Honeywell Systems and Research Center, Minneapolis, Minnesota under the direction of Mr. C. R. Vick, Director, Data Processing Directorate, Ballistic Missile Defense Advanced Technology Center. Mr. J. Scalf was the BMDATC project engineer for this contract; Ms. B. C. Stewart was the Honeywell/GRC program manager.

This report covers work from October 1976 to October 1977. Work on this task was performed by W. E. Boebert of the Honeywell Systems and Research Center and W. R. Franta of the University of Minnesota. These individuals also wrote a preliminary version of this report. The final version was written by W. E. Boebert. The bibliography was compiled by D. L. Hutchinson of the University of Minnesota.

This report presents the results of work in the area of payoffs (non-functional requirements) which derive from the use of distributed data processing in the data processing subsystems of BMD systems. The report states the objective of quantifiable or figure-of-merit payoffs, shows why that objective is not attainable at this time, and presents two approaches to achieve the objective. It also presents a preliminary description of the payoffs of distributed data processing in the form of a comparison with centralized data processing. All the results are presented in the context of an existing Systems Engineering framework.

This document is Volume II of the final report. Other volumes of the report are the following:*

Volume I	-	Management Summary AD B023 681
Volume III	-	DDP Rationale: The Technology Point of View
Volume IV	-	Application of DDP Technology to BMD: Architectures and Algorithms
Volume V	-	Application of DDP Technology to BMD: DDP Subsystem Design Requirements
Volume VI	-	Application of DDP Technology to BMD: Impact on Current DP Subsystem Design and Development Technologies
Volume VII	-	Application of DDP Technology to BMD: Experiments
Volume VIII	-	Application of DDP Technology to BMD: Research Performance Measurement
Volume IX	-	DDP Rationale: The Program Experience Point of View

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* Volumes V, VI, the appendix to Volume VII, and a section of Volume VIII were prepared by General Research Corporation.

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SECTION 1

BACKGROUND AND OVERVIEW

OVERVIEW

This volume is concerned with three distinct major research areas. The first is the need, in developing an analytic DDP design technology, for a complete Systems Engineering framework (to replace the inadequate waterfall chart) as a research context and model of the BMD system and DP subsystem life cycle; this research is presented in Section 2.* The second area is the derivation of a payoff quantification methodology (within the system context established in Section 2) as an early part of the DDP design theory; this research is presented in Sections 3 and 5. The third research area is the actual comparison of payoffs of centralized vs. distributed data processing (again within the systems context of Section 2); these results are discussed in Section 4. Key results are summarized in Section 6, and critical research issues and recommendations are presented in Section 7.

OBJECTIVES

Our effort throughout this task has been directed toward establishing the Ballistic Missile Defense (BMD) payoffs** which derive from the use of distributed data processing (DDP). In particular, we wished to compare

*In addition, a large bibliography of related research material has been provided as reference for interested research personnel.

**In this document "payoffs" and "nonfunctional requirements" are synonymous.

the payoffs derived from DDP with those which are obtainable from the other broad technological alternative for data processing subsystems--centralized data processing (CDP).

APPROACH

We initially adopted a straightforward and, in retrospect, somewhat naive approach: define a list of relevant payoffs, devise metrics and formulae by which these payoffs could be measured, and compute and compare the respective measures for DDP and CDP.

We then reviewed the various discussions of BMD payoffs which we obtained during the course of the contract. These discussions came from a variety of sources [312] and all contained a great many appeals to the intuition:

- Terms such as "growth," "reconfigurability," and "BMD effectiveness" were used interchangeably to describe the benefits that potential BMD systems may derive from a given technology, desirable objectives of a BMD system design activity, attributes of a specific BMD subsystem, and criteria for evaluating technology or implementation alternatives.
- The presentation of BMD payoffs as a "flat" or unstructured list ignored the clear existence of interrelationships, orderings, and dependencies; "growth" is not the same thing as "fault isolation," either in degree or kind.

A further attribute of BMD payoffs is obscured by compiling them into a simple list: certain payoffs exist or are manifest only during specific phases of BMD system life cycle, while others describe the worth of the system throughout its existence.

We noted these problems and began a wide-ranging and systematic review of the literature, still with the goal of seeking methods for devising formulae for quantitative assessment of BMD payoffs. In the course of this review, we found a large area of relevant work in the general field of Systems Engineering [258], especially in the publications of Hall [124], Hill [131], and Warfield [131, 320]. An examination of this work yielded the fundamental insight that a pursuit of formulae at this stage is wholly premature; it is not possible to express relations between variables in mathematical terms until a list of variables has been defined and the simple presence or absence of relations between them has been determined. This preliminary step, defining variables and determining meaningful intervariable relationships, is a non-trivial one in our case where we are attempting to define a relationship between a partially developed technology of great flexibility (DDP) and an extremely large and complex problem (BMD).

We accordingly revised our approach while still maintaining the goal of comparing CDP and DDP within the context of BMD payoffs. This revised approach, and the results to be presented in the subsequent sections, involved the following steps:

1. Definition of BMD Payoffs--We sharpened the definition of the term "BMD payoff" and placed our defined concept in the context of existing Systems Engineering methodologies.

2. Payoff Derivation Methodology--We developed an overview of methodology for the derivation of BMD payoffs and derived a structured set of payoffs using the methodology.

3. Comparison of CDP and DDP--We expanded the Hall-Hill-Warfield notation and used it to present a non-quantified comparison of CDP and DDP in terms of payoffs.

4. Approaches to Quantifiable Payoffs--We present two approaches which could result in a set of quantifiable BMD payoffs.

5. Further Research--We evaluated the results of this phase and considered the direction and specific nature of desirable further research in the area of BMD payoffs.

Many of the results, methods, and notations which are presented in the subsequent sections will appear straightforward to the point of being obvious. This is a consequence both of the scope of this task, which did not permit the development or exercise of tools to support elaborate examples, and the basic nature of Systems Engineering. This discipline imposes order and structure upon the solution process for complex problems. The order and structure which it imposes is natural and appropriate and, therefore, obvious in retrospect. It is by no means obvious during the early stages of a task when disjoint and partially-defined elements of problem and solution are surfacing in random order.

SECTION 2

DEFINITION OF BMD PAYOFFS

THE SYSTEMS ENGINEERING CONTEXT

Morphology

We begin with the general morphology of Systems Engineering which was first presented by Hall [124] and refined by Hill and Warfield [131]. This morphology is shown in Figure 1 [124], and the relationship between its terms and those of other frameworks, as presented by Sage [258], is given in Table 1 [258].

As can be seen in Figure 1, the Hall morphology gives a three-dimensional framework for Systems Engineering with the axes depicting the time, logic, and knowledge dimensions of the discipline. The time dimension is segmented by the major decision milestones. The segments between milestones are referred to as phases. The logic dimension describes the steps of the problem-solving procedure. The use of two separate dimensions for these two aspects of Systems Engineering results in a general structure in which any step (e.g., Systems Analysis) may be discussed in the context of any phase (e.g., Project Planning). This point will be discussed below in greater detail. The last dimension of the Hall morphology, the knowledge dimension, is organized somewhat arbitrarily into disciplines ranked according to the degree in which they embody formal

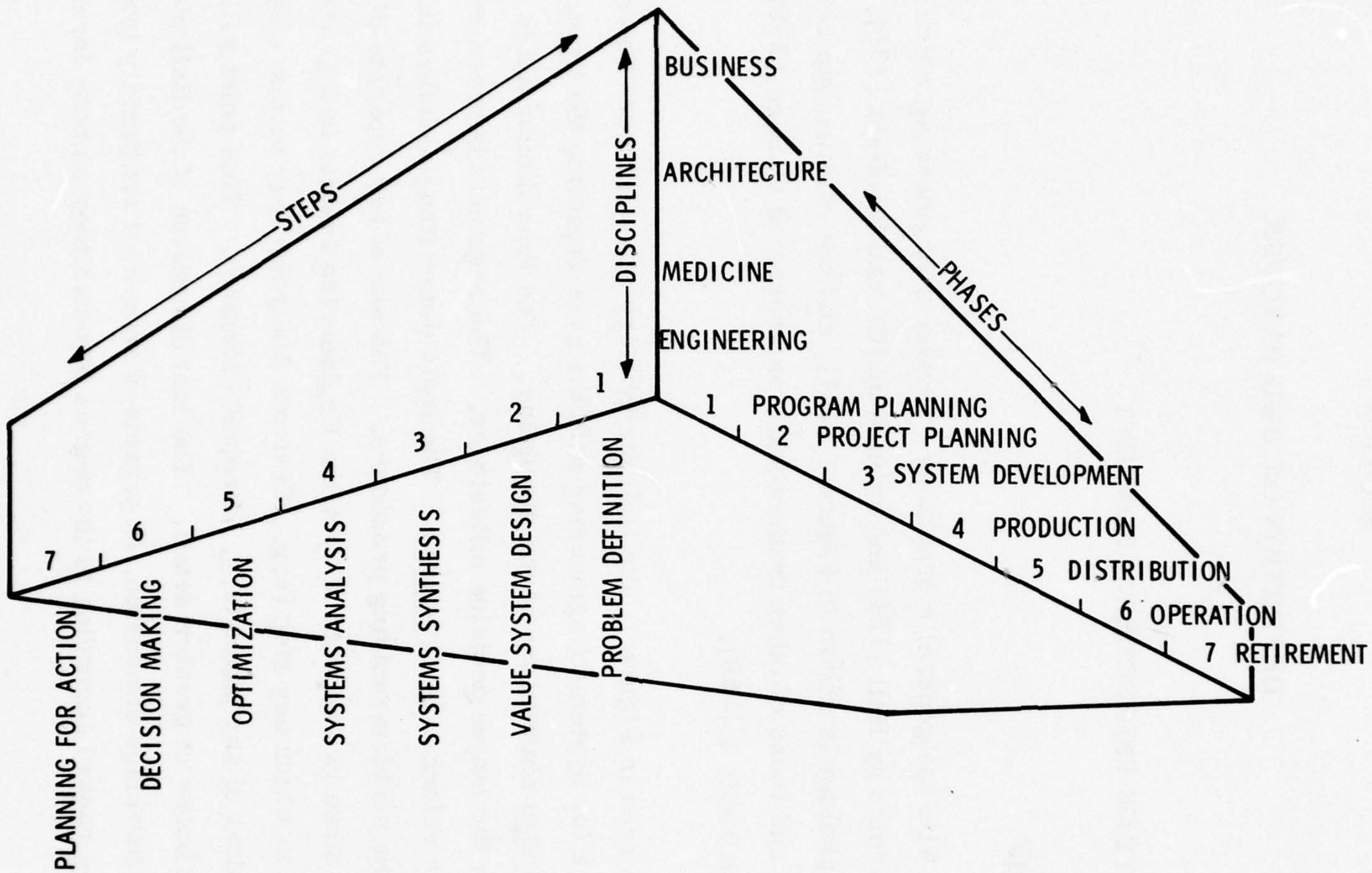

Figure 1. The Hall Morphology for Systems Engineering (Adapted from [124])

TABLE 1. COMPARISON OF FRAMEWORKS FOR SYSTEMS ENGINEERING (FROM [258])

AUTHORS OF THE PROPOSED STEPS									
Hall [124]	Hill and Warfield* [131]		Reisman, Kiley, and de Kluyer [248]	Miles [217]	Gibson [104-107]	Hutchinson [147]	Baker, Michaels and Preston [14]	Quade and Boucher [242, 243]	Kline and Lifson [170]
Problem Definition	Problem definition	Needs Constraints Alterables Societal sectors	Needs problem statement	Goal definition Problem statement	Goal development	Problem definition	Perception of need	Data collection Clarification of the problem Determination of the environment	Gather available information
Value System Design	Value system synthesis	Objectives Objectives Measures	Value model	Objectives and criteria development	Establish criteria for achievement of goals		Goal definition	Identification of objectives Determination of criterion	Formulate value model
System Synthesis	System synthesis	Activities or policies Controls or systems Activities measures Agencies	Synthesis of solutions	System synthesis	Development of alternate candidate solutions	Solution generation	Ø	Measurement of effectiveness of alternatives Investigation of alternatives	Synthesize alternate solutions
Systems Analysis	Systems analysis		Analysis and/or test	Systems analysis	Ø	Solution analysis	Policy analysis	Formulation of models Examination for sensitivities Consideration of deficiencies	Analyze and/or evaluate
Optimization	Optimization		Evaluation						Ø
Decision-Making	Decision making		Decision	System	Ranking of alternatives	Evaluation and choice	Alternative selection	Comparison of alternatives	Decide
Planning for Action	Planning for action		Ø	System implementation	Planning for action	Implementation	Resource allocation	Summary recommendations	Communicate

or mathematical techniques. Thus, any point within Hall's morphological box represents the application of a discipline (knowledge, or capability) to a step (an aspect of problem solving) within a phase (some period in the system *life cycle*). *This is shown in Figure 2.*

The knowledge dimension of the Hall matrix, as presented in literature, reflects an initial preoccupation of Systems Engineering with urban and societal problems and therefore must be modified for BMD applications. Such an exercise, although potentially valuable, is outside the scope of this task. Instead, we turn our attentions to the other two dimensions of the morphology: the time and logic axes.

Time

The time axis is broken down into seven phases. A program is defined and selected in the Program Planning phase of Systems Engineering. The specific projects to be carried out are identified in the Project Planning phase. In System Development, projects necessary to develop the system are implemented and production plans are made. System elements as well as the total system are produced, and plans are made for installation of systems in the Production phase. The system is installed and plans are completed for system operation in the Distributory phase. The system is put to useful work during the Operations phase. In the Retirement phase, the system is withdrawn from service.

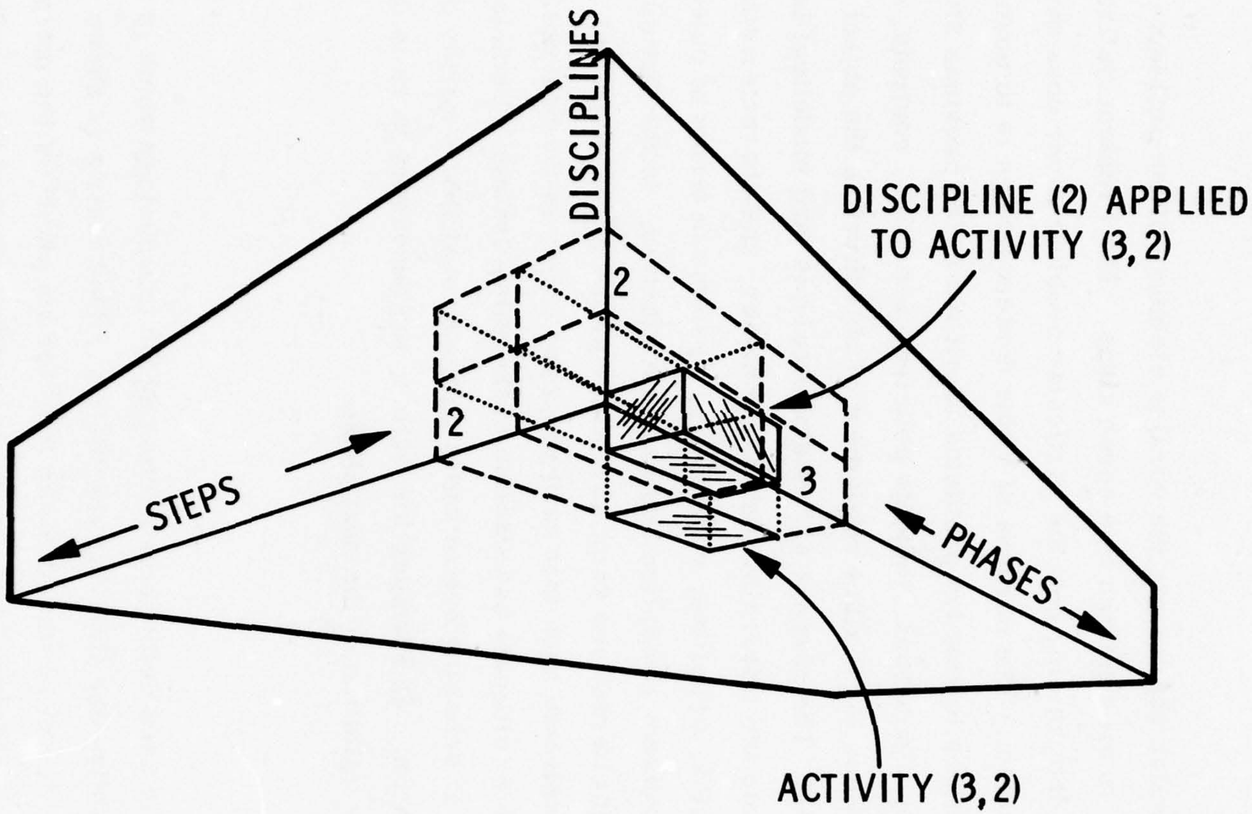

Figure 2. Use of the Hall Morphology To Depict The Application of a Discipline to an Activity (Adapted from [124])

Logic

The logic axis, which represents the various elements of the problem-solving process, is broken down into seven steps. The Problem Definition step is aimed at determining how the particular problem under consideration came to be a problem. The purpose of Value System Design is to postulate and clarify objectives to resolve problems identified in the previous step. Conceptualization of potential candidate policies, activities, controls, or whole systems which might allow attainment of objectives is the object of Systems Synthesis. The purpose of Systems Analysis (and modeling) is to develop insight into the interrelationships, behavior, and characteristics of proposed policies, activities, controls, or systems in terms of objective attainment and problem resolution and need satisfaction. In the Optimization or ranking of alternatives step, particular policy parameters and coefficients are selected such that each proposed policy is the best policy possible in terms of ultimate satisfaction of the value system. Decision Making is aimed at selecting one or more policies or systems worthy of further consideration. In Planning for Action, the necessary work is done to insure proper initiation of the next phase.

Activities

The time and logic axes define a projection of the morphology which is often discussed separately--the Hall Activity Matrix. This matrix is shown in Figure 3 [124]. It can be thought of as the "bottom plane" of the morphological box shown in Figure 1. As such, it is independent of the knowledge axis and is therefore independent of technology or the application area.

	STEPS → (LOGIC) / ↓ PHASES TIME	1 PROBLEM DEFINITION	2 VALUE SYSTEM DESIGN	3 SYSTEM SYNTHESIS	4 SYSTEM ANALYSIS	5 OPTIMIZATION	6 DECISION MAKING	7 PLANNING FOR ACTION
1	PROGRAM PLANNING							
2	PROJECT PLANNING							
3	SYSTEM DEVELOPMENT							
4	PRODUCTION (CONSTRUCTION)							
5	DISTRIBUTION (PHASE IN)							
6	OPERATIONS							
7	RETIREMENT							

Figure 3. Hall Activity Matrix (from [124])

An element of the matrix, which lies at the intersection of a phase and a step, is called an activity. Activities therefore are the use of some aspect of the problem-solving process during some period in the system life cycle. Activities are numbered according to their position in the matrix; thus Activity (3, 4) is the performance of the Systems Analysis step during the System Development phase.

The Hall Activity Matrix exhibits all possible activities but does not imply that all of them are performed or that they are performed in a fixed sequence.* It is therefore a superior notational device to simple milestone or "waterfall" charts which show a misleadingly linear sequence of events. In particular, Hall explicitly recognized that certain steps are performed iteratively across phases. Thus, Step 4 (Systems Analysis, or Deduce Consequences of Alternatives) may be repeated as Activities (1, 4), (2, 4), (3, 4), etc.; this shows the successive deduction of consequences of alternatives as a project moves from phase to phase.

The iterative nature of Systems Engineering was strikingly depicted by Hall in his Spiral Diagram (Figure 4 [124]). This shows the richest possible sequence of activities converging upon a solution or operational system; a segment of the spiral represents the successive applications of a step (element of the problem-solving process) with each application

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*The phases of the time dimension must naturally be followed, and steps which depend on each other (3 and 4, 2 and 6, etc.) must naturally occur in the proper sequence. The matrix, therefore, defines a partial ordering of activities.

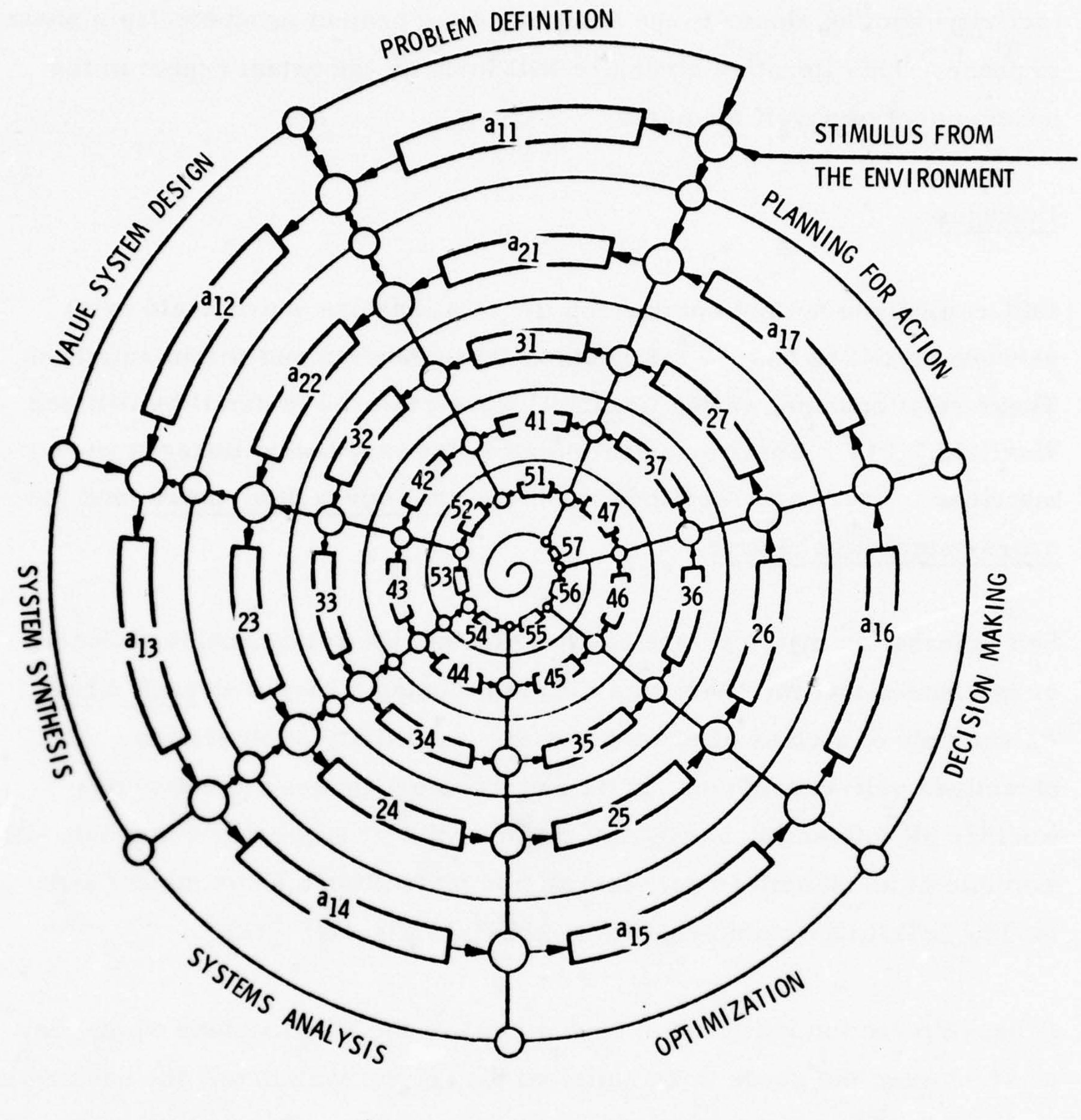

Figure 4. Hall Activities Represented as a Spiral Converging on a Solution (One revolution of the spiral is a phase; each segment is the successive application of a step.)

(activity) coming closer to the solution as the project proceeds from phase to phase. This iterative structure will form an important aspect in the development of payoff formulae.

Linkages

Hall recognized but did not develop the relationships which could exist between activities and the information flows between and within activities. These relationships, called linkages, were explored in detail by Hill and Warfield [131]. Their principal notation for expressing linkages were matrices. There are two kinds used: the self-interaction matrix and the cross-interaction matrix.

Self-interaction matrices are used to express the relationships, effects, or influences that members of a class of elements have with each other. An example of a class of elements within an activity is objectives. An objectives self-interaction matrix can therefore be used to determine whether objectives for a program conflict with or support one another. An example of an objectives self-interaction matrix for a short takeoff and landing (STOL) aviation program is shown in Figure 5 [131].

Cross-interaction matrices are used to show the relationships which may exist between the needs to be satisfied by a given system and the constraints imposed by the environment external to the system. An example of a needs/constraints cross-interaction matrix for a STOL program is given in Figure 6 [131].

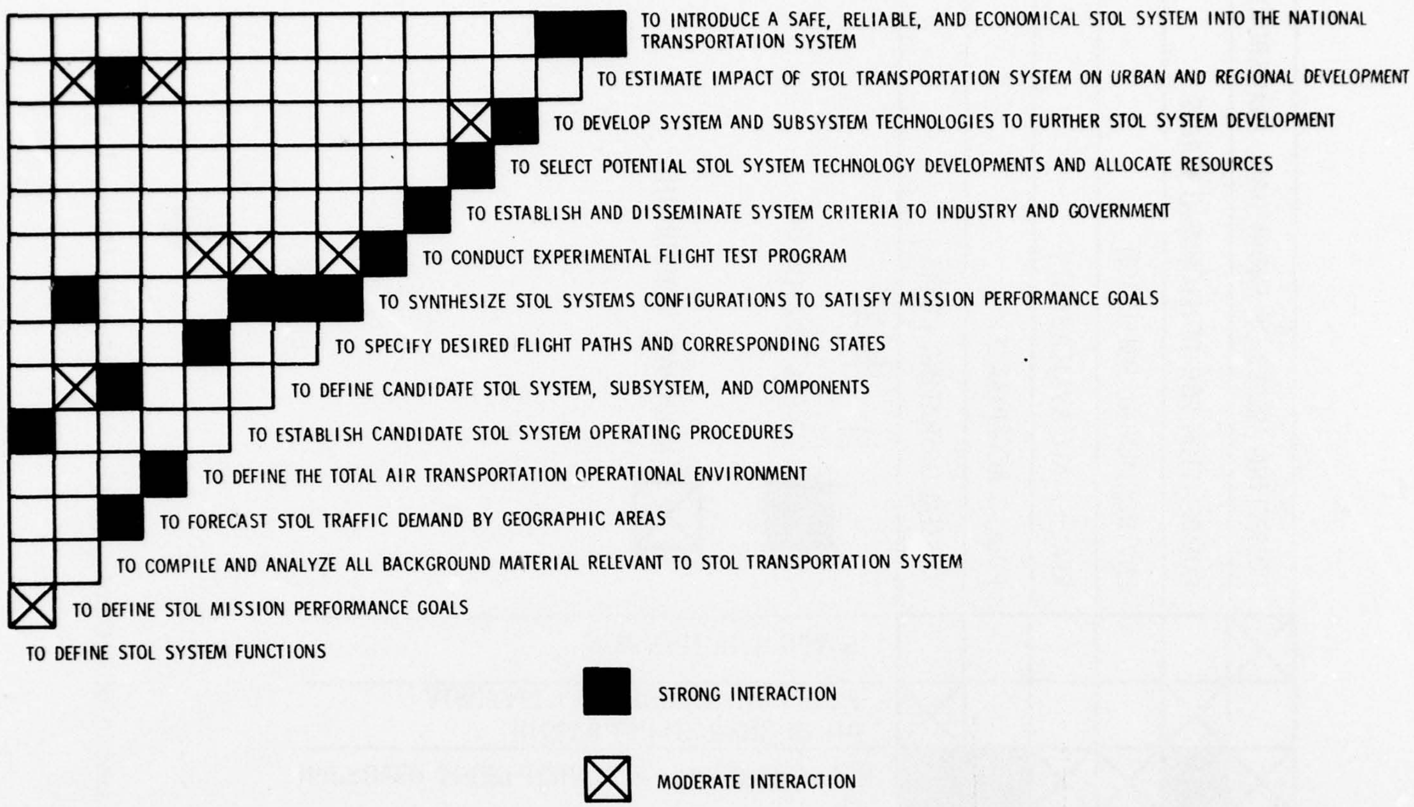

Figure 5. Example of a Self-Interaction Matrix (from [131])

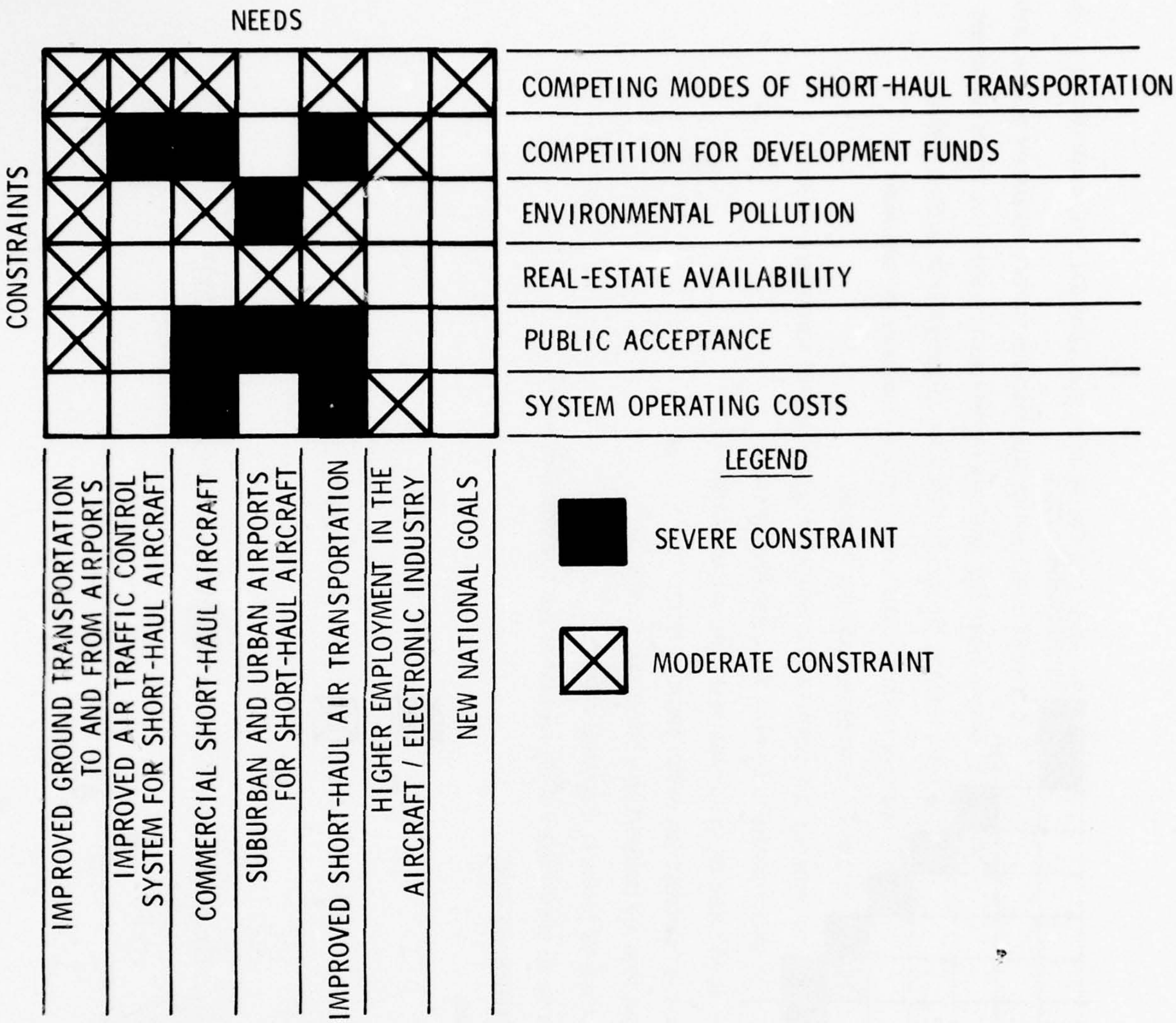

Figure 6. Example of a Cross-Interaction Matrix (from [131])

Self-interaction matrices, since they deal with a single class of elements, always occur within an activity. Cross-interaction matrices can either be used within an activity or to show linkages between activity. An example of a set of self-interaction and cross-interaction matrices for a single phase, Program Planning, is given in Figure 7. The number of matrices involved in just one phase gives an indication of the richness of the linkage structure for a meaningful program; we will return to this point when we present a BMD example.

The development of a linkage structure such as that in Figure 7 requires two classes of decisions: what the axes of the matrices are to represent (e.g., needs/constraints, alterables/constraints) and what relationship is to be depicted (e.g., "supports," "derived as a byproduct of," etc.).

PAYOFFS IN THE SYSTEMS ENGINEERING CONTEXT

Activities

Having adopted the Hall-Hill-Warfield schema as a descriptive device, we now restate our goal: compare CDP and DDP in the context of BMD payoffs in terms of activities and linkages.

We will begin by identifying the activities involved. The first problem which we address is to locate the phase in the Hall morphology which is appropriate for the task whose results are being presented. There are two reasonable alternatives: Program Planning (Phase 1) and Project Planning (Phase 2). The choice is made clear when we consider Hall's definition of Project Planning [124]:

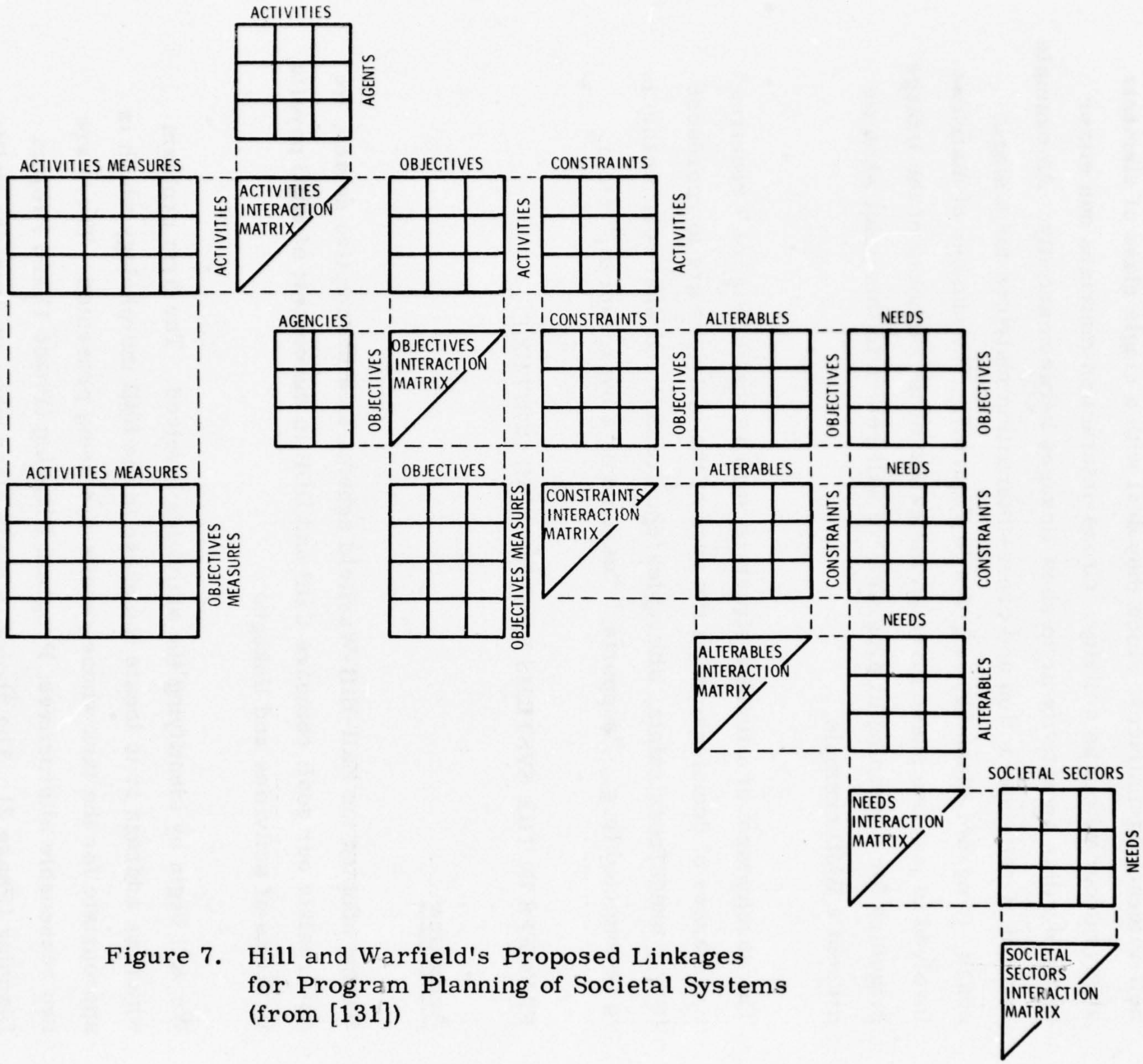

Figure 7. Hill and Warfield's Proposed Linkages for Program Planning of Societal Systems (from [131])

> "Project planning is distinguished from program planning by interest focused on just one project of the overall program."

If we regard the data processing subsystem as one aspect of the entire BDM system, then we are clearly engaged in Project Planning. The next, and more important, determination is what steps are involved.

The obvious connotation of the term "BMD payoff" with "benefit," "desired outcome," or "objective" leads us to place the derivation of BMD payoffs within Step 2 of the Hall matrix, Value System Design. Step 3, Systems Synthesis, has been done by default with the postulating of the alternatives of CDP and DDP. Step 4, Systems Analysis, will be performed when CDP and DDP are described or characterized in a manner which permits comparison. Step 5, Decision Making, is the step in which the actual comparison will be made. These steps, intersecting with our choice of Phase 2, gives the following definition of our task:

> Activity (2, 5), compare CDP and DDP, preceded by Activities (2, 4), deduce consequences of CDP and DDP and (2, 2), derive BMD Payoff Value System as basis for comparison.

These activities are shown in a Hall Activity Matrix in Figure 8, along with the linkages that they imply. This figure also shows the "missing linkages" which did not exist at the start of this task or which are not developed as part of it. The first missing linkage, and the one with the greatest consequences for our example, is the one leading from Activities (1, 1) and (2, 1), Problem Definition for Project Planning, and Problem Definition for Program Planning. The second missing linkage is the one which leads from our activities to later phases; this is a consequence of the scope of this task, which was to provide a meaningful comparison of CDP and DDP. This precluded any exploration of the relationship between payoffs and requirements. This subject falls properly under the Axiomatic Requirements Engineering (ARE) effort.*

Before we drop down to the next level of detail and start discussing specific notations and formats, we would like to observe that we have placed our goal of comparing CDP and DDP within the context of the Hall-Hill-Warfield schema. This schema uses the term "system" to describe the entity under discussion; we replace that with the more general term "technological alternative," by which it is inteded that "all systems which use this alternative." Our comparison, and the activities and linkages which it implies, will therefore not involve as rich or detailed a structure as a specific system would. We shall expand upon this point when we have presented the BMD example.

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*We did consider the relationship to a small degree and came to a preliminary conclusion that a requirement is a mandatory value or range of values for a quantifiable payoff.

REPRESENTATION OF BMD PAYOFFS

Importance of Notation

Given the impact of representation upon method, we will begin with a discussion of how the payoffs should be organized. This issue is exceedingly important because the decomposition and presentation effort is severely influenced by the tools employed for its realization. This is not a new or novel observation, nor is it unique to the BMD problem. For example, Whitehead and Russell apologize in the preface to the Principia for the abundant symbolism, but they point out that it was a necessary requisite to the task attempted. That is, without the formal tools of symbolic manipulation, their task was impossible. The limitation may essentially lie within the human mind. The same is true here, in that improper selection of tools can obscure the discovery, comprehension, and representation of payoffs.

Hierarchies

The most fundamental and prevalent means of organizing complexity, especially the complexity which is derived from interrelationships, is the hierarchy. This observation is elegantly made by Waller [314] and Simon [272, 275] and is supported by the ease with which we can find instances of hierarchies in a wide range of disciplines. We mention information theory (information flow), pure mathematics (lattice theory), biology (the hierarchical nesting of organs, cells, etc.), decision sciences (PERT, decision trees, etc.). Verbally, we may simply define a hierarchy as a partially-ordered structure of entities in which every entity but one is successor to at least one other entity, and every entity except the basic entities is a predecessor to at least one other entity.

Hierarchies as defined can be displyed via trees. We can expand upon the above so that the root entity is not unique; the tree becomes a directed graph with multiple roots. In summary, the term hierarchy simply denotes a partially-ordered set. To carry out the ordering, an ordering relationship is required. A proper ordering relationship for a hierarchy must be as follows:

- Binary--It must be between two elements.
- Irreflexive--The relation must not exist between an element and itself. The relation "equals" is not irreflexive; the relation "is the father of" is.
- Asymmetric--If entity A has the relation to entity B, entity B cannot have the relation to A. The relation "is subordinate to" is asymmetric.
- Transitive--If a relation holds between A and B as well as B and C, it must also hold between A and C.

A hierarchical structure which results from a proper ordering relationship possesses a set of attributes which contributes to its usefulness as a means of organizing complexity. In particular,

- It expresses relationships of association and disassociation.
- It expresses relationships of order or precedence.
- It permits consideration of subsets or subhierarchies which have the same organizing principle as the entire structure. This is

basic to effective human understanding of complexity because it enables piecewise consideration of a manageable number of entities.

The first two contribute to the selection process, the last to intellectual manageability. Thus, the general nature of hierarchies made them an obvious candidate for the method of organization of BMD payoffs. Their attractiveness was enhanced by their known correspondence with binary matrices [316] which permit the use of automated techniques for their generation and analysis.

Hierarchies were selected when a review of existing Value System Design techniques showed no viable alternatives [319] and when the application of the hierarchical structure to the BMD payoff problem produced a meaningful example.

Having selected the hierarchy as the organization for BMD payoffs, we must define the two aspects of the hierarchy: the elements and the relationship by which the elements are organized. We shall begin with a consideration of the elements of a BMD Payoff Hierarchy.

Elements of the BMD Payoff Hierarchy

This effort takes us to Step 1 of the Hall Activity Matrix, Problem Definition. An early positive result of our adoption of the Hall-Hill-Warfield schema was the way it clarified the cause of the initial difficulties we were having with payoffs: namely, that no Problem Definition steps had been performed or included in the scope of the contract. This defined the first of the missing linkages shown in Figure 8. As a consequence, Activity (2, 2), Value System Design, had to proceed without inputs. We will therefore digress from our main argument long enough to describe how we compensated for this missing linkage.

We began by recalling the purpose of the BMD payoff hierarchy: to provide a context in which CDP and DDP could be compared. The hierarchy should therefore possess at least two key attributes:

- It must be problem relevant; that is, it must properly reflect the nature of the BMD problem.

- It must be solution relevant; that is, it must contain information which can be related to technology.

We considered these two requirements for the hierarchy and reviewed the informal and intuitive payoff discussions which were the source documents for this task. As a result, we arrived at a preliminary partitioning of the BMD problem into three parts:

- A policy which embodies the stated will of the U.S. Government with regard to survival and sovereignty,

- A threat which seeks to negate that policy, either through outright attack or intimidation through threat of a successful attack, and

- A BMD system which actively enforces the policy in the face of the threat by reducing the effect of an outright attack or by preventing intimidation by being clearly able to reduce the effect of any potential attack.

STEPS → (LOGIC) / PHASES ↓ TIME	1 PROBLEM DEFINITION	2 VALUE SYSTEM DESIGN	3 SYSTEM SYNTHESIS	4 SYSTEM ANALYSIS	5 OPTIMIZATION	6 DECISION MAKING	7 PLANNING FOR ACTION
1 PROGRAM PLANNING	(NOT DONE)						
2 PROJECT PLANNING	(NOT DONE)	DERIVE BMD PAYOFFS	GIVEN: CDP AND DDP AS ALTERNATIVES	DEDUCE CONSEQUENCES OF CDP AND DDP		COMPARE CDP AND DDP WITHIN PAYOFF CONTEXT	
3 SYSTEM DEVELOPMENT							
4 PRODUCTION (CONSTRUCTION)							
5 DISTRIBUTION (PHASE IN)							
6 OPERATIONS							
7 RETIREMENT							

LINKAGE →
MISSING LINKAGE - - →

Figure 8. Linkages Used in this Report

Given this breakdown, it is clear that the BMD payoff hierarchy falls under the area of policy; the system (or, in our case, the technical alternatives for the implementation of the system) is the object being compared, and the threat is part of the outside environment. Placing payoffs as part of policy is also consistent with the previous informal and intuitive discussions of payoffs: each statement like "the system must adapt to new threats" represents a "common sense" generalization from an "obvious" but unstated policy about continued survival and sovereignty.

Placing the BMD payoff hierarchy in the policy area then exposes two lower-level problems:

- It is not clear what a policy looks like when organized or embodied in a payoff hierarchy.
- It is not clear how the payoffs in the hierarchy relate to the *mandatory* requirements which the system must meet.

The second problem is a manifestation of the second missing linkage in Figure 8, the one which should lend to activities in later phases. Establishment of this linkage is outside the scope of this task and thus we will only discuss the first problem.

We then return to the two attributes which we said the elements of hierarchy must have: problem relevance and solution relevance.

Solution relevance means that the payoffs must be useful to a practitioner in some technological area; it must enable him to gauge the quality of an existing solution (e.g., an element of a BMD system) or to select the most promising among several technological alternatives (such as CDP and DDP).

This in turn means that the payoffs must be expressed in technological terms, which are necessarily system dependent to a greater or lesser degree. This is an important point and one which we will return to when we discuss ways of achieving quantifiable payoffs. At the present stage of our discussion, we will recognize the system dependencies of payoffs by defining them to be measurable or observable attributes of a BMD system which correspond to (or embody, or are derived from) the policy which that system is to enforce in the face of the threat. Since our primary goal in this task deals with technological alternatives (CDP and DDP) for data processing subsystems, the payoffs we define will be measurable or observable attributes of data processing subsystems. Since no linkage to a Step 1 (Problem Definition) exists for this effort, we will derive the payoffs in our example by informal means from a simple policy of survival and maintenance of sovereignty. We now return to our main argument and continue the reasoning which led us to the particular hierarchy used in the example.

Organizing Principle of a BMD Payoff Hierarchy

We have selected the hierarchy as the organizing device for BMD payoffs and defined measurable or observable DP subsystem characteristics as the elements of the hierarchy. We also established that these elements (individual payoffs or individual DP subsystem characteristics) must relate to some policy. For purposes of our example and discussion we are satisfied with an informal, intuitive relation to a very general policy of national survival under attack and maintenance of national sovereignty under threat of attack.

We now consider a relationship between payoffs which will enable them to be organized into a hierarchy which can be mapped onto or related to the policy. The relationship must satisfy the hierarchical constraints of being binary, irreflexive, asymmetric, and transitive. A relationship which satisfies these constraints and corresponds to our intuitive notion of payoffs is the relation "significantly contributes to." This relation is also attractive because it supports the ultimate establishment of quantifiable payoffs: if payoffs A, B, and C significantly contribute to payoff D, then we can postulate a formula of the form $D=f(A, B, C)$ and begin to discuss the nature of $f()$.

LINKAGES TO OTHER ACTIVITIES

Description of Technological Alternatives

Our success with the hierarchical technique in organizing payoffs led us to try it for technological alternatives. We accordingly listed all the relevant characteristics of distributed and centralized processing technology and then tried pairwise comparisons with a variety of relations. No meaningful structures resulted, so in the interest of progress, we organized the characteristics in the form of a simple, unranked list.

Non-Hierarchical Interactions

The fact that the individual attributes of a technological alternative cannot be organized into a hierarchy does not mean that they are completely disjoint. Like other elements in the system development process, they may interact by means of relationships which would not yield a hierarchy, that is, relationships which are not binary, irreflexive, asymmetric, or transitive. Such non-hierarchical relationships can be represented by means of a self-interaction matrix.

A variety of interactions could be encoded in such a matrix. We decided that a useful one to depict would be the interaction or "coupling" which would occur between the characteristics promised by a technological alternative when an implementation using that alternative was attempted.

Such an interaction between two attributes exists when achievement of one occurs at the expense of another (negative interaction) or as a byproduct (positive interaction). For example, there is a positive interaction in the DDP technology between the characteristic "small processors" and "simple processors" since the implementation of one generally results in the other.

We felt that these "coupling" interactions would be useful in assessing the merits of a particular technological alternative. In order to represent the possible range of interactions, we had to expand the original Hill-Warfield values of "strong" and "weak" [131] into five values. Our values and the meanings they assume for this set of interactions are the following:

- Strong Positive--One characteristic is very often a byproduct of the other.
- Weak Positive--One characteristic is sometimes a byproduct of the others.
- Interdeterminate--The characteristics relate in a manner not known now.

- Weak Negative--One characteristic must sometimes be traded off against the other.
- Strong Negative--One characteristic must very often be traded off against the other.

The Ends/Means Matrix

We return now to our basic goal of comparing CDP and DDP within the context of BMD payoffs. Our use of the Hall-Hill-Warfield schema leads us to represent this comparison as a linkage in the form of cross-interaction matrix. We therefore have two things to determine: what the dimensions of the matrix should represent, and what interaction should be encoded in the matrix. We will begin by considering the dimensions. One dimension of the matrix must clearly be the characteristics of the technologies being compared. These characteristics represent the means provided by that technology. For our example we will consider the characteristics of CDP and DDP as constituting one partitioned set of means so that comparison can be made with reference to a single matrix.

The obvious choice for the second dimension of the matrix is the individual BMD payoffs. Each element of the cross-interaction matrix then depicts a potential relationship between an attribute of a given technological alternative and a BMD payoff. This leads to another choice in the organization of the matrix: whether the payoff dimension should list all the payoffs or only those at the bottom level of the hierarchy. We chose to list only those at the bottom level for the following reasons:

- The nature of the relation "significantly contributes to" forces a gross ordering on the elements of the payoff hierarchy. This ordering proceeds from the general (at the top) to the specific (at the bottom). The bottom-level payoffs are therefore the most specific and detailed elements of policy that are available for comparison.

- The hierarchy itself already shows the "flow" of the interactions through the higher-level payoffs. Thus a technology attribute which interacts with a bottom-level payoff is already placed in context by the existence of the hierarchical relations between the bottom-level payoff and the higher-level (or more general) payoffs.

In addition to making this choice for the dimensions of the cross-interaction matrix, we extended the Hill-Warfield notation in the same manner as we did for self-interaction matrices. The resulting five values and the meanings assigned to them in the Ends/Means Matrix are as follows:

- Strong Positive Interaction--The given means very often support achievement of the given end.

- Weak Positive Interaction--The given means sometimes support achievement of the given end.

- Indeterminate Interaction--The given means may support or may conflict with achievement of the given end.

- Weak Negative Interaction--The given means, when used to achieve some <u>other</u> end, will sometimes conflict with the achievement of the given end.

- Strong Negative Interaction--The given means, when used to achieve some other end, will very often conflict with the achievement of the given end.

The complete linkage structure which resulted from the above reasoning is shown in Figure 9. This is the linkage structure which will be used in the BMD example--the results of our original goal of comparing CDP and DDP.

Observations on the Linkage Structure

We developed a linkage structure in this task for two reasons: to provide an orderly comparison of CDP and DDP, and to give a basis for the development of quantifiable payoffs. It is therefore only a fragment of the linkage structure which would be necessary to describe the BMD problem. The scope of a full-fledged linkage structure can be gauged by examining the example presented in Hill and Warfield [131]. Their example deals with the linkages that would exist only in the Program Planning phase of a project to develop a commercial STOL capability. This example uses 18 matrices which show the interactions between eight different classes of elements in such a program: Objectives, Objective Measures, Activities, Activity Measures, Agencies, Constraints, Needs, and Alterables. The largest matrix (Activities interacting with Activities Measures) is 45 x 41. Their STOL program is considerably simpler than the BMD data processing problem, and the level of detail they provide is insufficient for any meaningful engineering judgments. This indicates that we have but set a direction and made a beginning; we feel that the direction is a proper one.

STEPS → (Logic) / (Time) ↓ PHASES		1 PROBLEM DEFINITION	2 VALUE SYSTEM DESIGN	3 SYSTEM SYNTHESIS	4 SYSTEM ANALYSIS	5 OPTIMI-ZATION	6 DECISION-MAKING	7 PLANNING FOR ACTION
1	PRO-GRAM PLAN-NING							
2	PROJECT PLAN-NING		DERIVE BMD PAYOFFS	GIVEN: CDP AND DDP AS AL-TERNATIVES	DEDUCE CONSE-QUENCES OF CDP & DDP		COMPARE CDP & DDP WITHIN PAY-OFF CONTEXT	

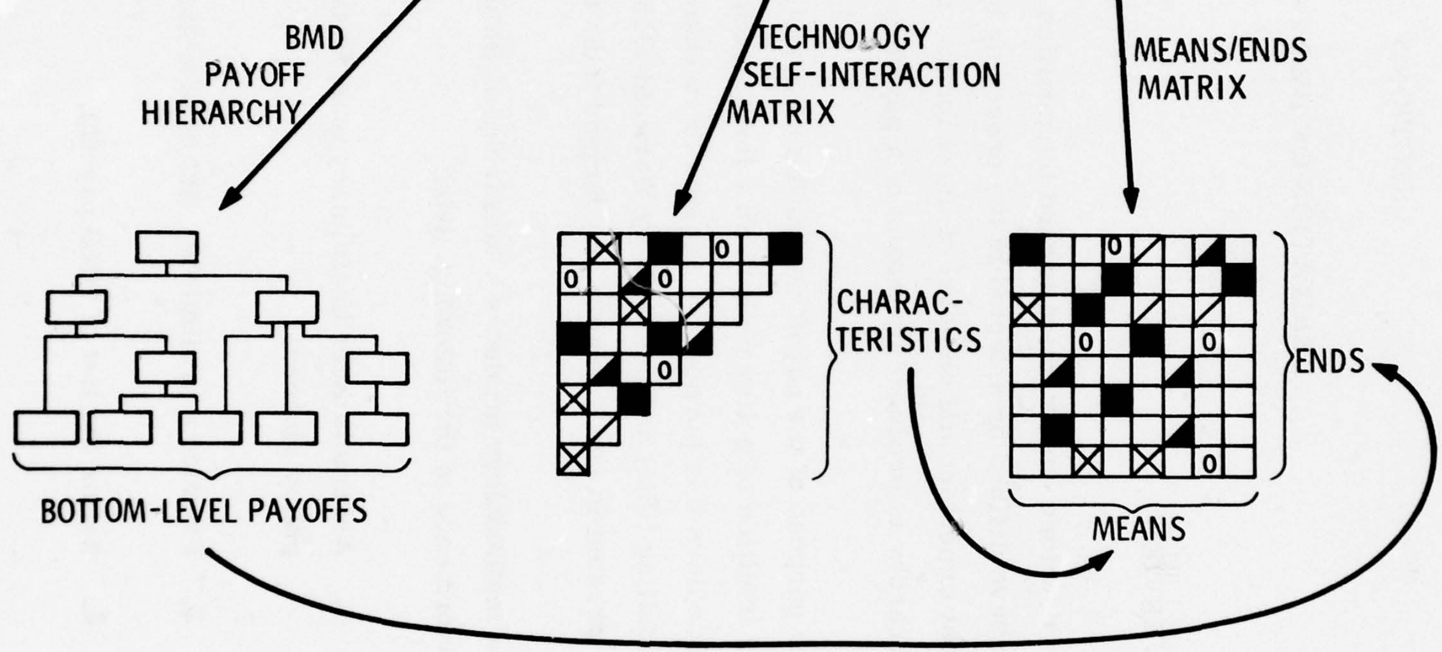


Figure 9. Linkages and Notations Used in this Task

SECTION 3

DERIVATION OF BMD PAYOFFS

OVERVIEW

We now turn our attention toward the addition of content to the forms which we have defined or selected in the preceding sections. We begin with the most important and complex of these forms, the payoff hierarchy. This hierarchy is produced by means of a payoff derivation methodology.

The purpose of the payoff derivation methodology is to capture the knowledge and intuition of policy makers in a form which is technologically relevant. To achieve this purpose we adapted the technique of interpretive structural modelling (ISM) as developed by Warfield [315]. The specific steps which we present in our overview are derived from those of Waller [314].

The methodology produces a hierarchy of BMD payoffs through the performance of the following steps:

1. Assemble interdisciplinary team of technologists and policy makers.

2. Produce a preliminary list of potential BMD payoffs.

3. Refine the list of BMD payoffs.

4. Do a pairwise comparison of individual payoffs using the relation "significantly contributes to" and encode the results of the comparisons in a binary matrix.

5. Convert list of payoffs and the encoded comparisons to a hierarchy.

6. Evaluate and refine the resultant hierarchy.

These steps are expanded in the following subsection.

PAYOFF DERIVATION METHODOLOGY

Assemble Team

The great strength of ISM is its ability to consolidate the knowledge and intuition of individuals from a variety of backgrounds [314]. This strength should be used in any meaningful BMD payoff exercise. As a minimum, the team should consist of policy makers, individuals with experience in problem characterization (i.e., simulation and operations research), and representatives of technology areas which will be involved in the achievement of the payoffs. The team should be presented with the policy for the BMD system of subsystem for which the payoffs are being derived. If a policy is not available, the team should be given the responsibility of establishing that policy in its form of an interrelated structure of decomposed elements, i.e., a payoff hierarchy.

Produce Preliminary Payoff List

The team should then generate a preliminary, unstructured list of payoffs and their associated definitions.

Refine Payoff List

The preliminary list is reviewed by the team for completeness and redundancy. Once the team is satisfied that a complete list has been produced and that no payoffs are defined twice under different names, the payoff definitions should be made as precise as possible.

Do Pairwise Comparison

The team then undertakes a pairwise comparison of all the payoffs in the list. For each pair of payoffs, the team determines the presence or absence of the relationship "significantly contributes to." The results of the comparison are encoded in a binary matrix [314].

Produce Hierarchy

The binary matrix is then converted to the graphic form of a hierarchy for purposes of review by the team. This conversion can be done manually [314] or by automated techniques [314, 315, 316, 317]. Automated techniques are recommended because the manual ones are tedious, time-consuming, and error-prone.

Evaluate

The team then reviews the hierarchy and decides whether it satisfactorily represents their knowledge and intuition.

Refine

It is very likely that the early hierarchies will contain many apparent anomalies, in that the results of the individual payoff definitions and their pairwise comparisons will not correspond to the team's intuitive notion of a "right" structure. Expressed in BMD terms, typical anomalies which occur in ISM exercises [314] include:

- Payoffs which occupy counterintuitive positions in the hierarchy. Payoffs which are "obviously" high level may end up at low levels in the hierarchy and vice-versa. This requires review of the pairwise comparisons. A major advantage of ISM in handling this class of anomaly is the manner in which it focuses the team on consideration of intellectually manageable pairwise comparisons rather than unguided review of an entire complex structure [314].
- Inability to produce a single hierarchy. The set of all pairwise comparisons may result in two or more disjoint hierarchies [314]. This is an indication that not all the payoffs in the list are interrelated by the relation "significantly contributes to." This may result from redundant payoffs where essentially the same thing is defined in different words. Another cause of disjoint hierarchies is the omission of a necessary payoff which links the hierarchies together.

Resolution of the anomalies will require the repetition of some of the previous steps. This iterative aspect of ISM gives another reason for the use of automated tools to convert the sets of pairwise comparisons (binary matrices) into graphic hierarchies.

USE OF THE METHODOLOGY

Overview

We shall now illustrate the payoff methodology by producing an example of a payoff hierarchy. This example hierarchy will also provide the basis for the comparison of DDP and CDP in the context of BMD payoffs. The example is limited by the contract scope and the resultant reliance on manual techniques for hierarchy generation; it is, however, comprehensive enough to show the power of the ISM technique as well as the inherent advantages of DDP.

The Starting Problem

The very first observation which was made by the example payoff team was the absence of an available BMD policy to guide the production of the hierarchy. This was a reflection of the point, which we already noted, that the scope of the task was in the middle of the Hall Activity Matrix and that in particular (in his terms) there did not exist a defined linkage between the Hall activities which involve Problem Definition and this activity.

The team accordingly decided to initiate their effort by postulating top-level payoffs which would be generic in that they would correspond to a wide range of intuitively "reasonable" policies. This enabled work to progress at the expense of clarity of definition.

Establishing these top-level payoffs began by postulating a life-cycle model of a BMD system. This model is defined in terms of intervals and transitions (Figure 10). An interval was defined as a period in the life cycle and a transition as an event which marks the boundary between two intervals. The life-cycle model begins with the transition of commitment, which is the decision to deploy, and continues through deployment and use. It therefore does not include any events or activities associated with research and development or program planning. This choice of span of the life cycle was made so that the model and the policy derived from it would include the periods during which the payoffs are manifest rather than the periods when the payoffs are defined or made possible. Thus a research and development activity may develop a technology which makes fault tolerance possible, and a program planning activity may select that technology; but the system will not manifest fault tolerance until the system exists. In Hall's terminology, we would say that payoffs from technology (which are the class we are considering in our example) only occur or manifest themselves during Phases 3 through 6: System Development, Construction, Phase In, and Operations. Our life-cycle model and its relation in the Hall phases is given in Figure 11.

Having defined an appropriate life-cycle model, the team then decided to proceed in a top-down fashion. They accordingly began with a top-level payoff of sovereignty and survival and defined two second-level payoffs:

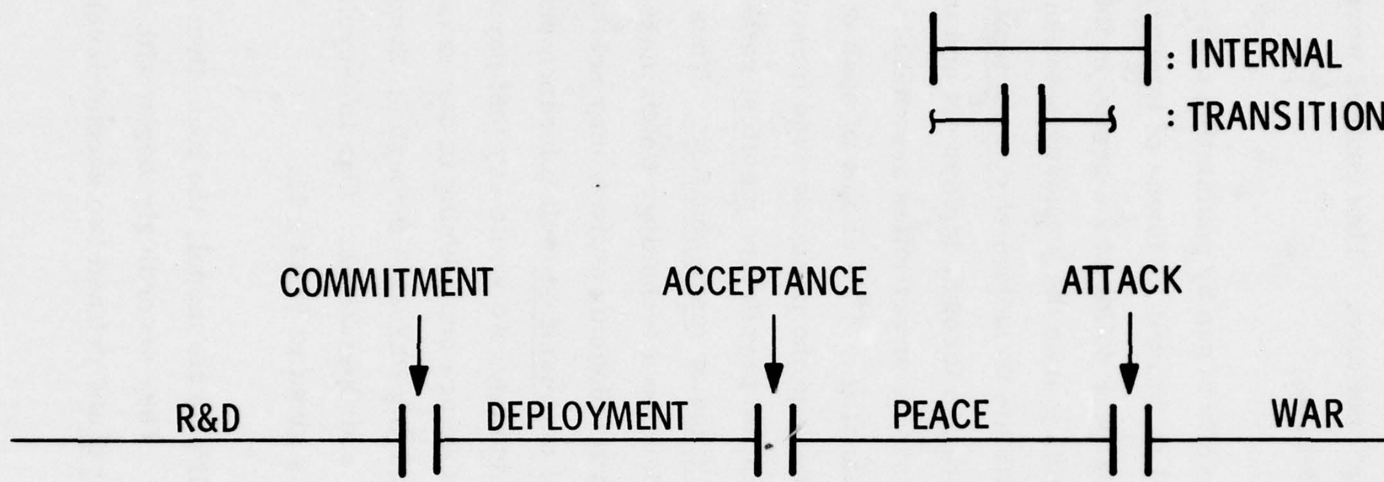


Figure 10. BMD System Life-Cycle Model Used to Overcome the Starting Problem

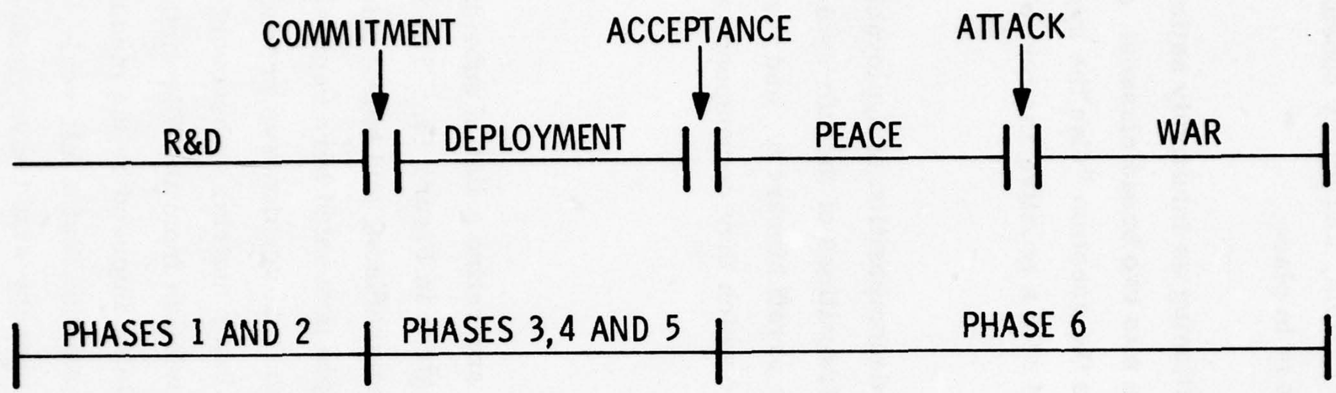


Figure 11. BMD System Life Cycle Related to Hall Phases

deployability and utility. Deployability subsumes all policy aspects having to do with the deployment of a BMD system, and utility subsumes all policy aspects of the system once it is in place.

The team regarded this initial partitioning as intuitively satisfying since it segregated all policy considerations into two broad classes: one associated with a positive answer to the question "Can the system be deployed?" and the other associated with a positive answer to "Will the system serve a useful purpose?"

The team then performed a further decomposition of deployability and utility, guided by the intervals and transitions of the life-cycle model. The resulting top three levels of the payoff hierarchy, and the intervals or transitions of the life-cycle model to which they correspond, are shown in Figure 12.

Development of the Hierarchy

The team then proceeded to develop and refine a list of subsidiary payoffs. The resulting payoff definitions are given in Figure 13. The individual payoffs were subjected to pairwise comparison, and hierarchies were produced and evaluated. The example presented here represents the third revision of the hierarchy. The first version was produced by means of a manual transformation from a binary matrix; subsequent versions were manipulated directly. This deviation from the ISM methodology was caused by the extreme clerical problems imposed by the manual method. It was clear from even this limited exercise that a full-scale, computer-supported ISM effort on the payoff hierarchy would have yielded significant

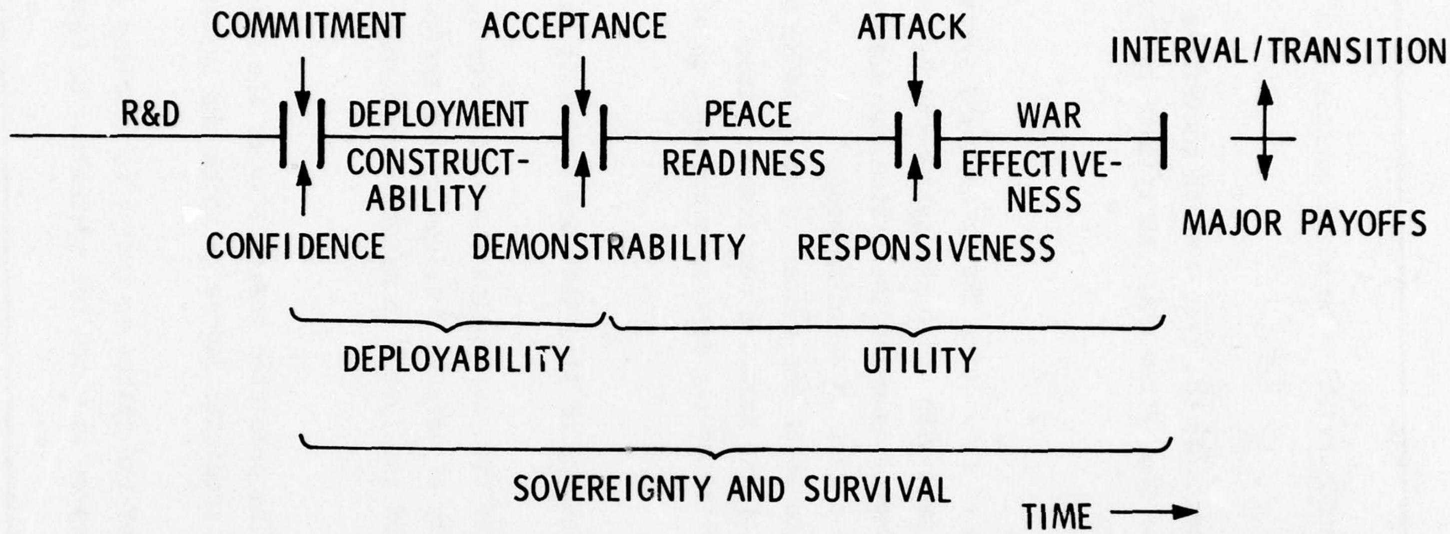


Figure 12. Top Three Layers of Payoffs and Portions of Life Cycle within which They Are Manifest

Top-Level Payoff

National sovereignty and survival--The basic purpose of a BMD system.

Second-Level Payoffs

Deployability--All aspects of the system which contribute to deployment.

Utility--All aspects of the system which contribute to its usefulness once in place.

Third-Level Payoffs

Confidence--The degree of confidence that a deployed system will work.

Constructability--The ease with which the system can be built.

Demonstrability--The degree to which the system can demonstrate its capability in a test or exercise mode.

Readiness--The extent to which the system is ready to go to war.

Response--The quality of the system's response to attack.

Effectiveness--The quality of the defense subsequent to attack.

Fourth-Level Payoffs

Availability--The percentage of time that the system is up and ready to defend.

Longevity--The period of time over which the system resists obsolescence.

Performance--The quality of defense provided by the system.

Tenacity--The ability of the system to maintain performance under pressure.

Fifth-Level Payoffs

Foreseen Feasibility--The predicted feasibility of the system.

Foreseen Adequacy--The predicted degree to which the system will enforce the policy.

Security--The ability of the system to resist non-nuclear attack.

Maintainability--The degree to which the system can be kept in a fault-free state.

Figure 13. Payoff Definitions

Graceful Degradation--The ability of the system to avoid collapse as elements are lost.

Graceful Saturation--The ability of the system to avoid collapse under overload.

Sixth-Level Payoffs

Foreseen Low Risk--The predicted absence of risk of the deployment of the system.

Foreseen Correct Functionality--The predicted correct behavior of the deployed system.

Foreseen Adequate Performance--The predicted adequacy of the deployed system.

Predictable Performance--The degree to which the performance of the deployed system can be predicted.

Low Cost--The economy with which the system can be deployed.

Short Time--The speed with which the system can be deployed.

Fault Tolerance--The degree to which the system minimizes the effect of a fault.

Reliability--The absence of faults.

Functional Adaptability--The ability to change functionality in response to new threats.

Growth--The ability to handle increased numbers of existing threats.

Loss Tolerance--The ability to continue operation as elements of the system are destroyed.

Bottom-Level Payoffs

Predicable Cost--The degree to which the cost of deployment can be predicted.

Foreseen Low Cost--The predicted economy of deployment.

Foreseen Short Time--The predicted speed of deployment.

Figure 13. Payoff Definitions (continued)

Predictable Time--The degree to which the speed of deployment can be predicted.

Technically Robust--The success of the system does not depend on the success of a small number of technical breakthroughs.

Alternate Implementation--The ability of a given design to be built several ways.

Function Testable--System elements can be tested on a per-function basis.

Mass Production--Small system elements can be built in large numbers.

Rapid Integration--The speed with which system elements can be combined.

"Slice" Testable--The system can be tested by an interception of a single object.

Formally Verifiable--Critical software can be proved.

Fault Detection--The ability of the system to locate a fault.

Fault Isolation--The ability of the system to contain a fault.

Reconfiguration--The ability to move load and functionality to alternate system elements.

Maintainer Quality-- The effectiveness of the maintenance organization.

Processor Reliability--Freedom from fault of the processors.

Link Reliability--Freedom from fault of the interprocessor links.

Programmability--The ease with which software can be written for the system.

Functional Modularity--The ease with which new functions can be added to the system.

Load Modularity--The ease with which capacity can be added to the system.

Capacity--The number of objects the system can defend against.

Correctness--The ability of the system to perform proper actions upon attack.

Timeliness--The ability of the system to perform quickly upon attack.

Real-Time Adaptability--The ability of the system to deal with unforeseen events.

Figure 13. Payoff Definitions (continued)

Loss Detection--The ability of the system to locate destroyed elements.

Loss Isolation--The ability of the system to minimize the effect of destroyed elements.

Real-Time Reconfigurability--The ability of the system to move load and functionality off of destroyed elements.

Element Survivability--The number of system elements which avoid destruction.

Figure 13. Payoff Definitions (concluded)

results by permitting the calculation and presentation of results for a much larger and more detailed set of payoffs. A frequent source of change in the development of the hierarchy was the inability of the team to agree on the relationship between a bottom-level payoff and those above it. This inability to agree would cause a detailed examination of the definition of the bottom-level payoff. The examination, in turn, often resulted in a decomposition of that payoff into a subhierarchy. The net result was a great deal of iteration, far more than the manual methods could handle.

SECTION 4

DDP RATIONALE

OVERVIEW

We are now prepared to present the results whose achievement formed our original goal: the comparison of CDP and DDP. These results will use the formats, notations, and structure which resulted from the effort described above. There are three results: the BMD payoff hierarchy, the technology characteristics self-interaction matrix, and the Ends/Means Matrix.

PRESENTATION OF RESULTS

BMD Payoff Hierarchy

The BMD payoff hierarchy which resulted from our ISM exercise is shown in Figure 14.

Technology Self-Interaction Matrix

The matrix in Figure 15 shows the interactions which exist between various characteristics of data processing technology. The interaction between two characteristics is that which we defined when we presented the linkage structure: whether the act of implementing a system using this technology implies a relationship or "coupling" between characteristics of the

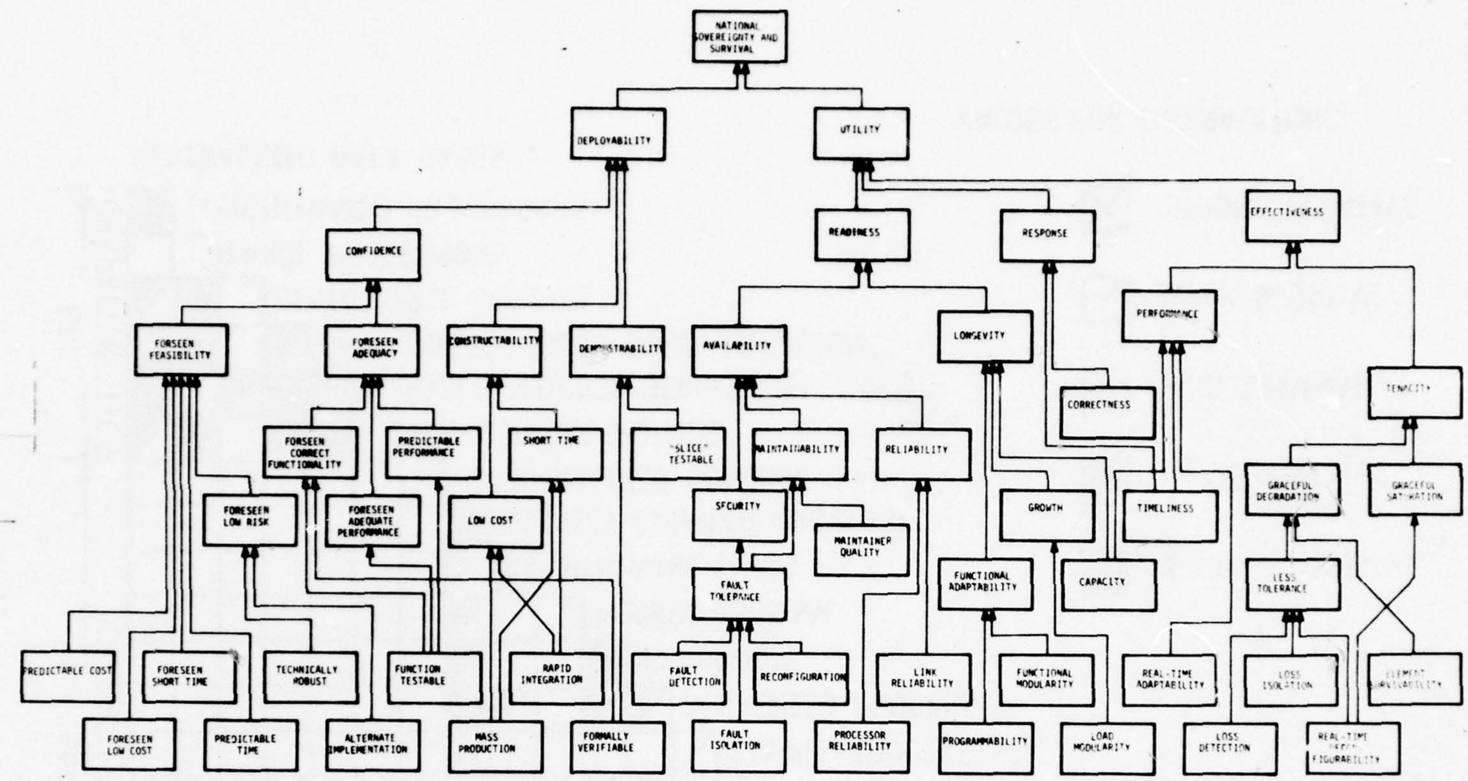


Figure 14. BMD Payoff Hierarchy

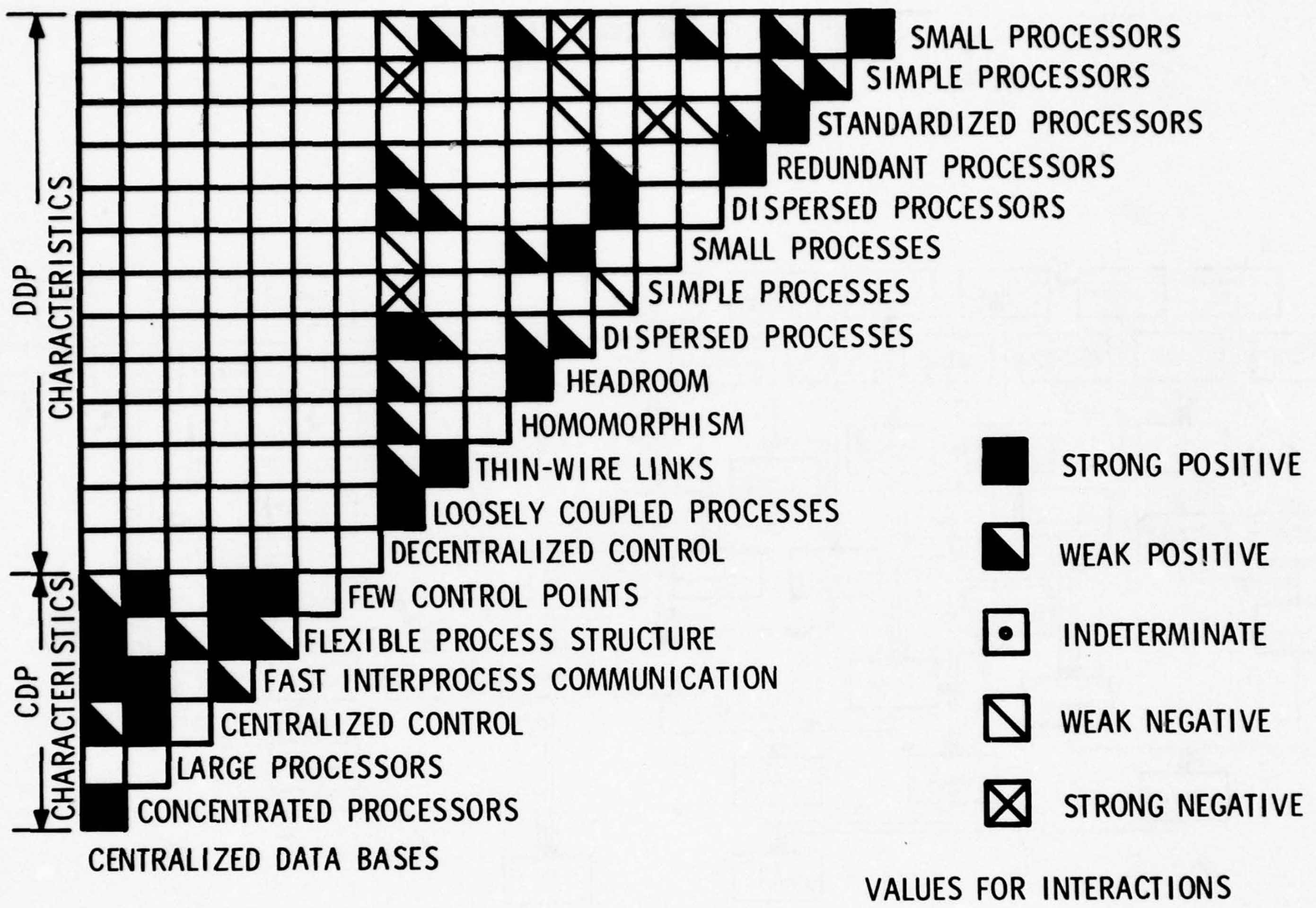


Figure 15. Technology Self-Interaction Matrix

technology. This "coupling" can be positive as when a characteristic occurs as a byproduct of another, or it can be negative, as when a conflict exists.

An example of a conflict is the interaction between standardized processors and simple processes; setting a standard for processors means that some of them may not have the special capabilities required to support certain processing needs. This in turn means that some processes would have to be more complex than necessary because they would be implemented on inappropriate processors. Therefore the characteristic of standard processors interacts negatively with the characteristic of simple processes when a system implementation is attempted.

For the sake of simplicity of presentation, we show all characteristics of data processing technology in a single matrix, regardless of whether they are derived from CDP or DDP; the matrix is divided into zones to show the two technological alternatives.

Ends/Means Matrix

The relationship between technology and payoffs is shown in the matrix of Figure 16. As with the self-interaction matrix, we show both CDP and DDP technical characteristics on one axis and divide the matrix into zones in order to permit comparison.

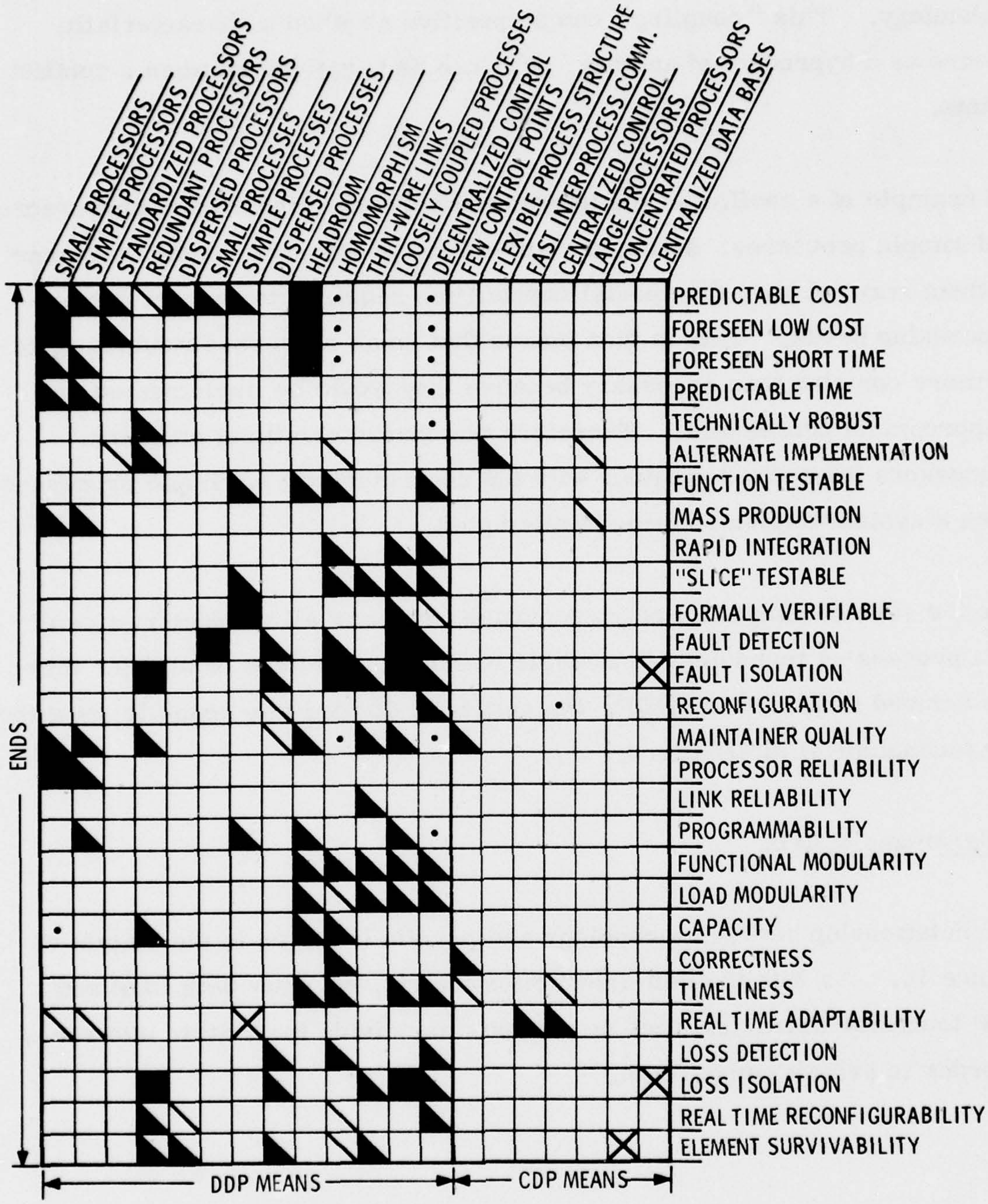


Figure 16. Ends/Means Matrix

Justification of Strong Positive Interactions

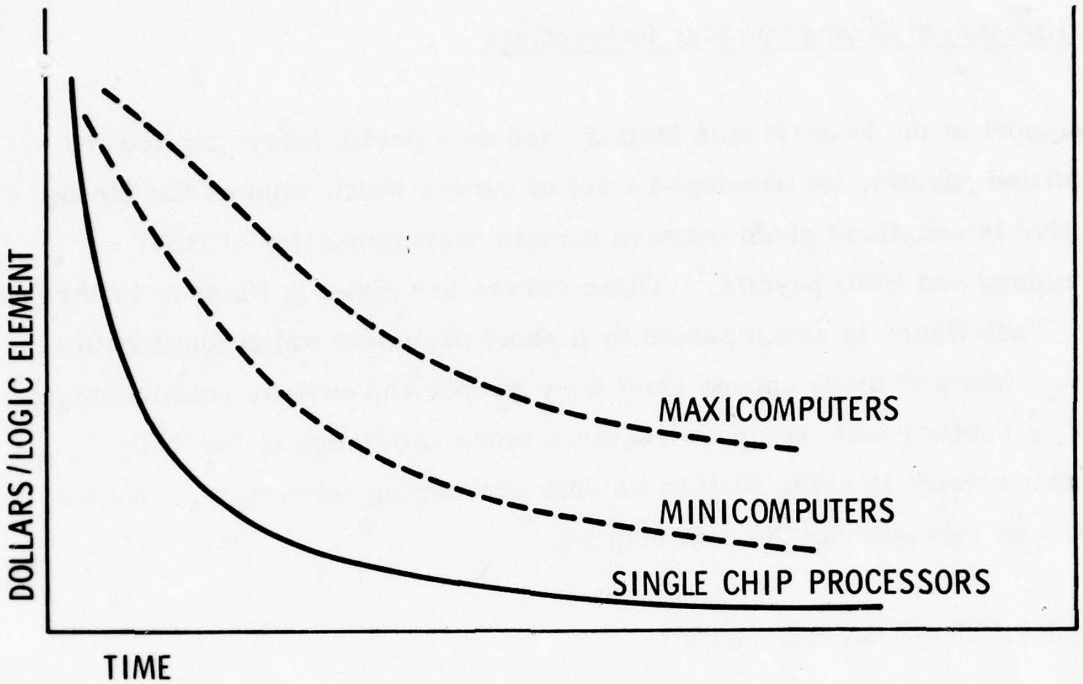
In support of the Ends/Means Matrix, and as a preliminary step toward quantified payoffs, we developed a set of curves which support the strong positive interactions given between certain characteristics of DDP technology and BMD payoffs. These curves are given in Figures 17 through 26. Each figure is accompanied by a short argument which justifies its form. Many of these curves show very simple and obvious relationships; greater subtlety and exactness requires more knowledge of the BMD construct which is using DDP in its data processing subsystem. We will expand on this point in the next section.

OBSERVATIONS ON RESULTS

Overall Observations

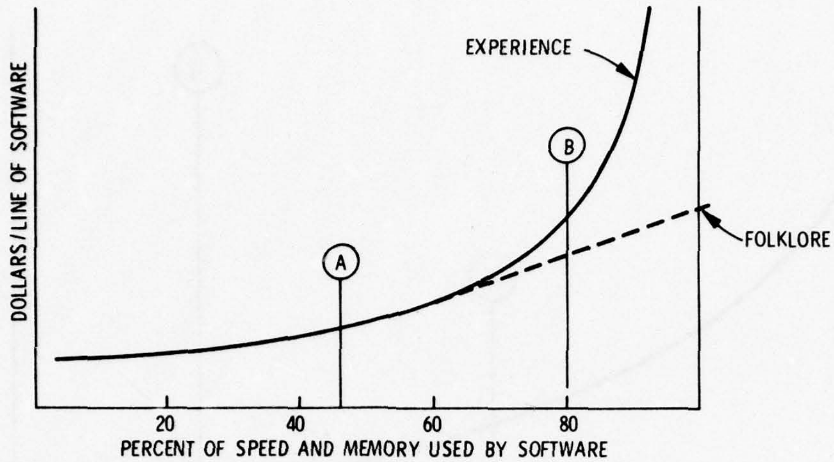
As we observed when we presented the linkage structure, the scope and focus of this task kept us from developing results of adequate richness. The lack of a firm and stated BMD policy (in the sense of the problem break-down into policy, threat, and system) forced us to postulate "generic" or "common sense" payoffs in order to derive a payoff hierarchy. We feel that the outcome represents a minimum reasonable payoff hierarchy, one from which broad conclusions can be drawn.

The technology characteristics which we present are limited to the data processing technologies of CDP and DDP. Review of actual data processing development efforts such as Safeguard and the Modular Missile-Borne Computer indicate that there are interactions (trade-offs) between <u>all</u> the



The cost of electronic components is dropping at a nonlinear rate. Single-chip, general-purpose processors have wide potential use in consumer products. This permits them to be made in larger quantities than other components, and their price drop is accordingly faster than average. Minicomputers and maxicomputers contain a lesser or greater labor component in their cost; this prevents them from dropping in cost as rapidly as the single-chip processors. Since labor costs are rising approximately linearly, the gap in price (for an equivalent gap in functionality) between single-chip processors and mini/maxicomputers should therefore widen.

Figure 17. Justification for Strong Positive Interaction between Small Processors and Low Cost



(A) PERCENT OF SPEED AND MEMORY USED BY ENSEMBLE OF PROCESSORS FOR A TASK

(B) PERCENT OF SPEED AND MEMORY USED BY UNIPROCESSOR TO HANDLE SAME TASK

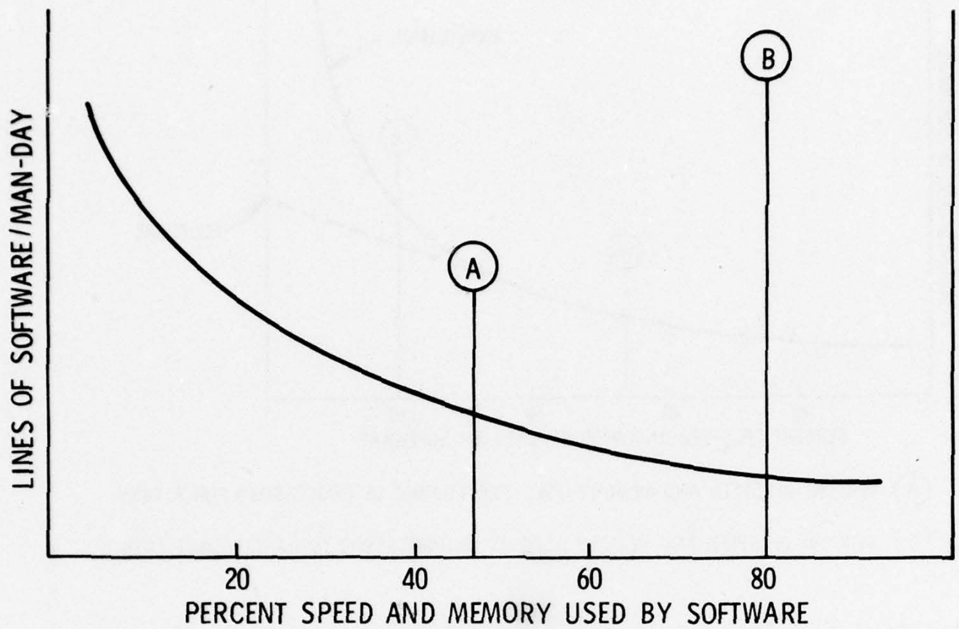
The cost of developing software rises nonlinearly as a function of the hardware resources used by the software. The nonlinearity becomes most pronounced when the software uses more than 50 percent of the hardware capacity. There are two mechanisms which cause this to occur:

1. Programmers are forced into unstructured programming in order to obtain the last tiny percentage of efficiency.

2. The unstructured software, combined with a lack of capacity to accommodate test routines, seriously complicates the test problem.

Use of an ensemble of processors to handle a task which would require 80 percent of the largest known uniprocessors will, as shown in the curve, permit each processor in the ensemble to be economically programmed.

Figure 18. Justification for Strong Positive Interaction between Processor Headroom and Low/Predictable Software Costs

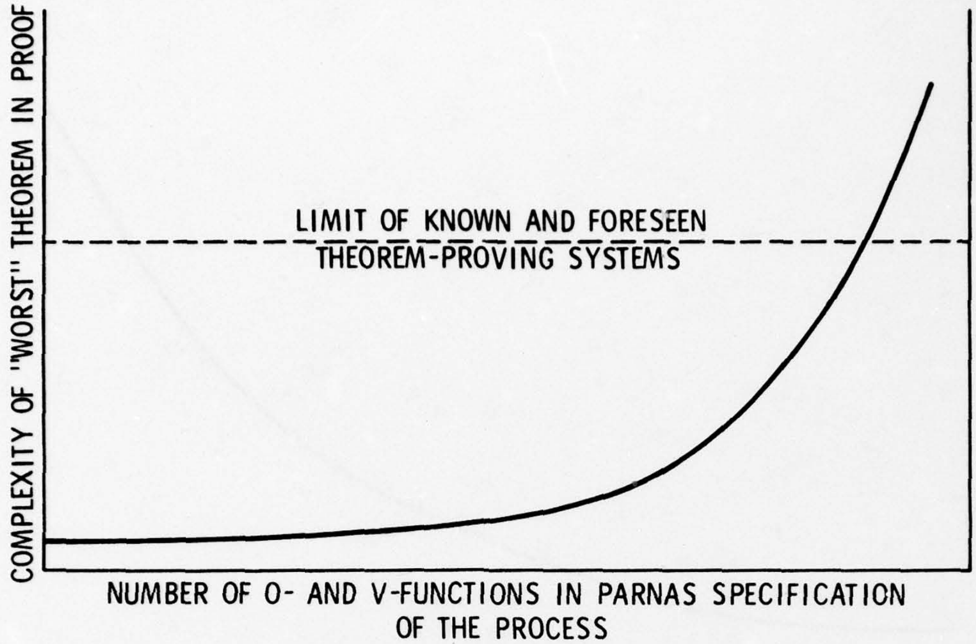


(A) PERCENT OF SPEED AND MEMORY USED BY ENSEMBLE OF PROCESSOR FOR A TASK

(B) PERCENT OF SPEED AND MEMORY USED BY UNIPROCESSOR TO HANDLE SAME TASK

The productivity of a software project in terms of lines of software per man-day will be the reciprocal of the curve for dollars/line of software since labor rates make money a linear function of time. The software productivity will be the governing factor on speed of overall system development time since software is always the critical-path item.

Figure 19. Justification for Strong Positive Interaction between Processor Headroom and Short Development Time

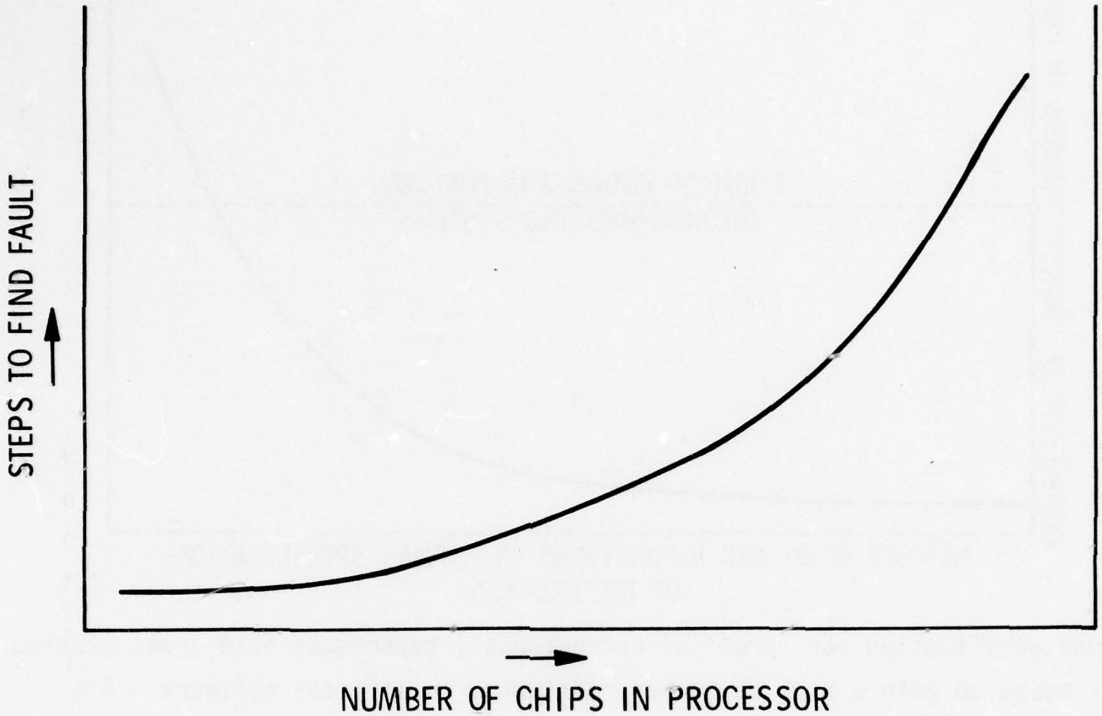


Formal verification (or "proof of correctness") techniques hold great promise as a means to gain a high degree of confidence in critical software. All formal verification techniques involve the generation of assertions about correct program behavior which in turn yield theorems which must be proved within some axiomatic systems. These theorems are proved using partially or fully automated theorem-proving systems. These systems are limited in the amount of complexity they can handle in a theorem.

The amount of complexity in a theorem appears to be a nonlinear function of the complexity and number of interactions in the program from which the theorem was derived. Program or process complecity can be charactized in terms of the number of functions in a Parnas specification for the process.

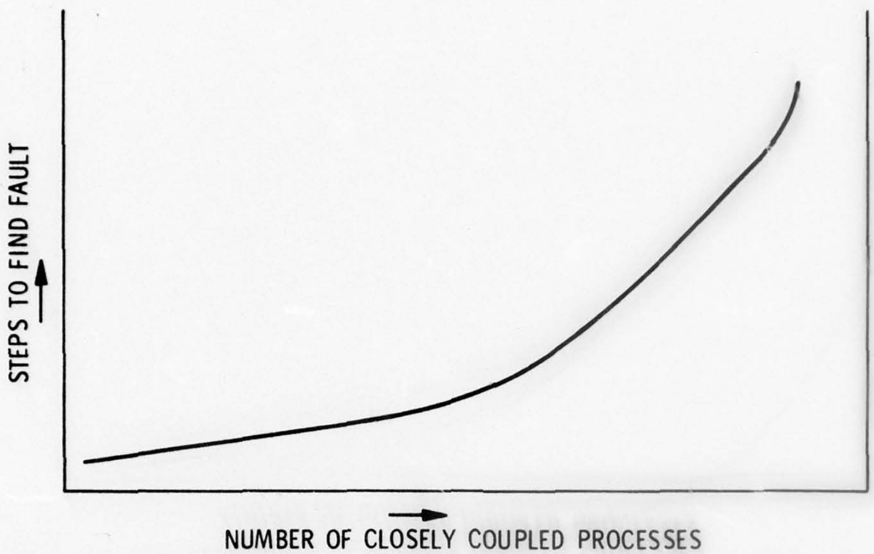
A given task performed by a large number of simple processes may therefore be formally verifiable whereas the same task performed by a single process may not.

Figure 20. Justification for Strong Positive Interaction between Simple Processes and Formal Verifiability



The number of steps required to locate a fault to the chip level increases exponentially with the number of chips in the processor because the number of processor states which must be considered increases exponentially with the number of chips. This phenomena can be overcome by built-in facilities for parallel test; these facilities will generally only be provided for processors resident on ground-based platforms.

Figure 21. Justification for Strong Positive Interaction between Small Processors and Fault Detection



Two processes are closely coupled when one process can modify the state space of a second. This contrasts with loosely coupled processes which can only send messages; the second process then has the option of ignoring a message and thereby "protecting" its state space from the first process.

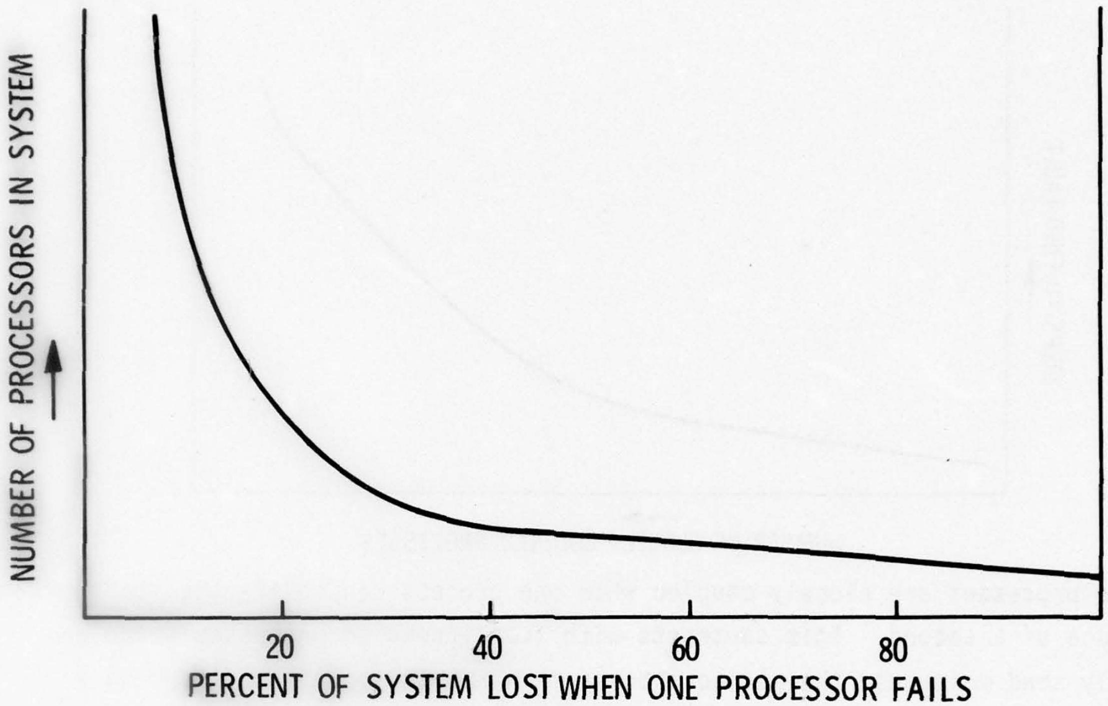
A fault may be the result of an action by a single process, two closely coupled processes working as a unit, etc. This requires consideration of a single process, pairwise, triples, etc. There are therefore:

$$\binom{n}{1} + \binom{n}{2} + \binom{n}{3} + \cdots \binom{n}{n} = 2^n$$

tests which must be made for n closely coupled processes.

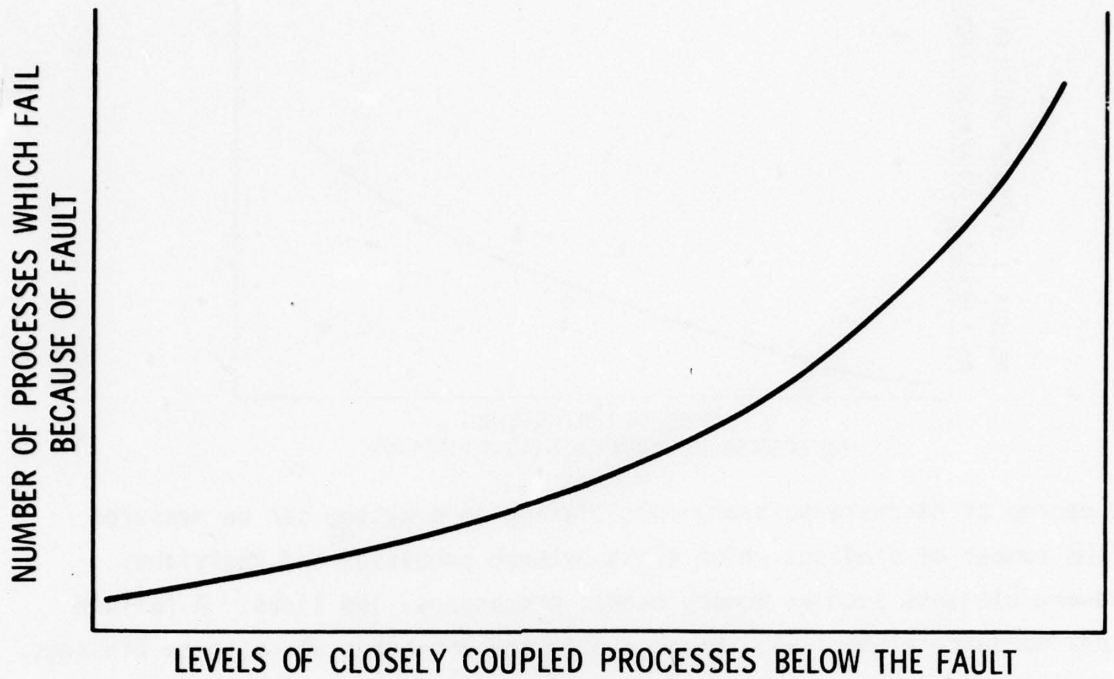
Loosely coupled processes do not present this problem because they do not combine into units for purposes of stimulating a fault. This is because they are able to maintain separation of their state spaces. Faults can then be located by a process-by-process search strategy.

Figure 22. Justification for Strong Positive Interaction between Loosely Coupled Processes and Fault Detection



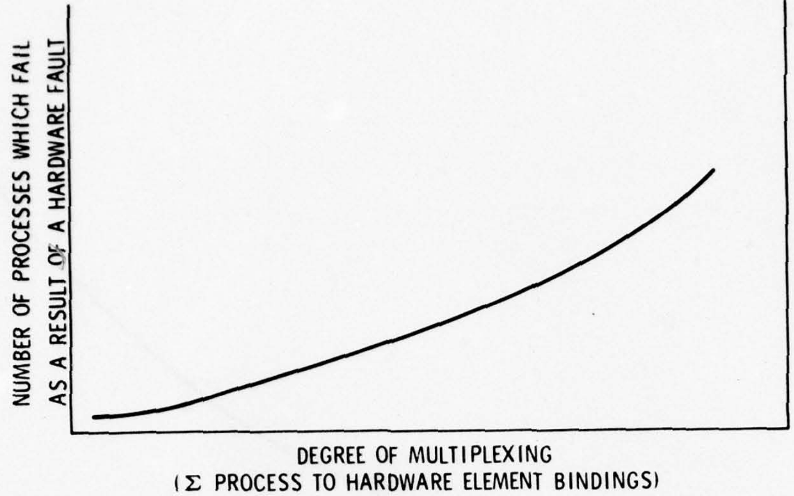
Proper design of interprocessor links can prevent processor failures from propagating across links. The impact of a processor failure then becomes inversely proportional to the number of processors in the system.

Figure 23. Justification for Strong Positive Interaction between Redundant Processors and Fault Isolation/Loss Isolation

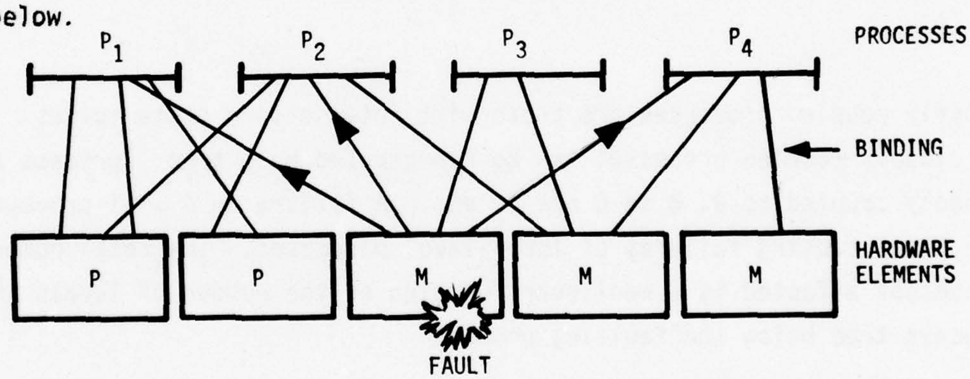


Closely coupled processes are those with intersecting state spaces. A set of closely coupled processes can be represented by a tree: process A is closely coupled to B, B to C and D, etc. A failure in A will propagate down the tree, causing failures of lower-level processes. The total number of processes affected is a nonlinear function of the number of levels in the process tree below the faulting process.

Figure 24. Justification for Strong Positive Interaction between Loosely Coupled Processes and Fault Isolation/Loss Isolation



The degree of hardware-software multiplexing in a system can be measured by the number of bindings which exist between processes and individual hardware elements such as memory banks, processors, and links. A failure in any hardware element will propagate to the processes along these bindings. Thus if a memory bank is bound to (shared by) three processes, failure of that bank will cause all three processes to fail. This is shown in the diagram below.



Our curve is shown as slowly rising instead of linear. This is because highly multiplexed systems use processes to allocate and manage hardware elements. A failure of element A may then propagate to process p, which manages B. Failure of p is the same as the failure of B since B cannot be used or allocated to any other process.

Figure 25. Justification for Strong Positive Interaction between Homomorphism and Fault Isolation

NUMBER OF COMPONENTS	PROBABILITY OF COMPONENT SUCCESS						
	.9	.99	.999	$1\text{-}10^{-4}$	$1\text{-}10^{-5}$	$1\text{-}10^{-6}$	$1\text{-}10^{-7}$
10	.35	.904	.99	.999	$1\text{-}10^{-4}$	$1\text{-}10^{-5}$	$1\text{-}10^{-6}$
10^2	$3\text{x}10^{-5}$	.37	.905	.99	.999	$1\text{-}10^{-4}$	$1\text{-}10^{-5}$
10^3		$4\text{x}10^{-5}$	.37	.905	.99	.999	$1\text{-}10^{-5}$
10^4			$5\text{x}10^{-5}$	.37	.905	.99	.999
10^5				$5\text{x}10^{-5}$	.37	.905	.99
10^6					$5\text{x}10^{-5}$	.37	.905

PROBABILITY OF PROCESSOR FAILURE

The above table gives the probability of processor failure as a function of the number and reliability of its components. The striking relationship is the one between the probability of failure and the number of components.

Figure 26. Justification for Strong Positive Correlation between Small Processors and Processor Reliability

technologies: sensor, platform, kill, communications, and data processing. A full set of linkages would show these technologies interacting with themselves and each other and would thereby make all the implications of all the technology options visible to the planner. This is another aspect of a point which we have made previously: that the definition and understanding of payoffs becomes exact and complete only in the context of a BMD construct. We shall return to this point when we discuss the ways that quantifiable payoffs might be achieved.

Comparison of CDP and DDP

Even at this beginning stage, there exists enough information in the Ends/Means Matrix to draw some basic conclusions about the relative applicability of CDP and DDP to the BMD problem:

- DDP provides a richer set of characteristics than CDP. There are more means available to achieve a given set of ends through use of interconnected smaller processors than through single large ones. Some of these means, such as those associated with raw computational power, are provided by both CDP and DDP; others, such as the ability to disperse processing, are unique to DDP.

- The means which DDP provides support the ends which a BMD system must achieve. This support comes in two broad areas: the application of decentralization and dispersion to a system which must deal with a hostile environment, and the application of a building-block approach to complex and evolving systems.

SECTION 5

TOWARD QUANTIFIABLE PAYOFFS

OVERVIEW

We stated at the beginning of this report that we would not be able to present quantifiable payoffs at this time. We considered the problem of quantifiable payoffs in significant depth before we reached that conclusion. Most of our consideration of the problem took the form of devising ways to reach the goal of quantifiable payoffs. Our results and conclusions in this area are only indirectly concerned with the goal of comparing CDP and DDP for BMD; however, we believe that they are interesting and important.

FEASIBILITY OF QUANTIFYING PAYOFFS

Classes of Payoff Measures

Warfield [320] lists three categories of objectives/benefits (payoffs) and ways in which their achievement may be measured. In order of decreasing rigor, they are:

- Quantifiable--measured by deterministic or probabilistic techniques. Deterministic techniques compute values from formulae; probabilistic techniques involve the taking of samples and interpolating or extrapolating by means of classic estimation methods.

* Binary-Event--measured by logical techniques. A binary-event payoff is one which is defined in terms of the desired response to a defined stimulus. It is called binary-event because the stated response (event) either occurs or does not. Logical techniques therefore resemble checkout or debugging methods.
* Qualitative--measured by axiological techniques. A qualitative payoff is one whose measurement involves a value judgement.

Measures During Phase 2

At this point in time (Project Planning), all payoffs are at best qualitative and many are not defined in any satisfactory way at all. This is a direct consequence of the absence of "systems context"--specifics about the BMD construct which could be used in formulae or binary-event descriptions. Thus at this phase we can state the existence of a payoff called Reconfigurability; we can place it in the context of the payoff hierarchy and show how it contributes to higher-level payoffs. However, we cannot state what exactly is being reconfigured, where reconfiguration should occur, or what event constitutes a satisfactory demonstration of reconfiguration.

Measures During Phase 6

During Phase 6 (Operations), all payoffs are either quantifiable or binary event. This is a direct result of the existence of a complete systems context (in the form of an operational system) in which payoffs can be defined, described, and measured. Quantifiable payoffs can be computed by means of formulae which use the measured behavior of the elements of the system, and binary-event payoffs can be measured by tests using the system or simulations whose correspondence to the actual system can be verified. Thus there exists one activity during which payoffs are quantifiable.

THE EVOLUTION OF PAYOFFS

Movement from Qualitative to Quantifiable

The two states of the payoff hierarchy discussed in the above paragraphs can be viewed as the beginning and end of an evaluation of the payoff hierarchy. The essence of this evolution is the transformation of the payoffs from qualitative to quantifiable (or binary-event).

Thresholds in the Evolution

Within this movement there are three major thresholds which a specific payoff crosses as it becomes progressively better defined. They are:

- The Definitional Threshold--At this threshold a reasonable informal definition of the payoff is available and intuitive curves can be drawn showing the relationship between it and its contributing payoffs or, if it is a bottom-level payoff, what its definition would be in terms of proposed system elements (processors, links, etc.).

- The Simulation Threshold--Here it is possible to develop a definition of the payoff in terms of the behavior of a model of the proposed system. The correlation between the model and reality will be more or less suspect at this time.
- The Verification Threshold--The final threshold is crossed when enough detailed system context and real system elements are available to verify the correctness of models used to demonstrate or compute payoffs or to demonstrate or compute payoffs through actual test.

Means of Achieving the Evolution

We believe that the above discussion makes it clear that the payoff hierarchy evolves as the system evolves: the more that is known about the system, the more that is known about the payoffs. We have identified two ways in which the necessary detailed system knowledge can be obtained. One way is as a natural byproduct of the development of the system. The other way involves a specific exercise separate from system development. Both ways are described in succeeding subsections.

NATURAL PAYOFF EVOLUTION

Overview

In this subsection we will present an approach to the evolution of payoffs from qualitative to quantifiable/binary event. The approach is called the "natural" evolution because it occurs as an integral part of the overall system development. Its description is straightforward because of Hall's basic insight in developing the Activity Matrix: that the steps may be repeated iteratively through the phases. The natural approach then consists of repeating the Value System Design step at each phase. The activities which thereby result ((1, 2), (2, 2), (3, 2), etc.) will each involve a refinement of the payoff hierarchy, using the systems context which has been developed during the previous phase. The resulting linkages are shown in Figure 27.

Thresholds

We have also identified the various activities during which the major thresholds of payoff definition should be crossed. These are:

- The Definitional Threshold--This should be crossed during Activity (2, 2), Value System Design for Project Planning. This, it should be noted, is the activity in which we placed the task of this report. We also acknowledge that we had not crossed the definitional threshold in our results. This is a consequence of the missing linkage from Activities (1, 1) and (2, 1) and the desire that the results of this contract be independent of any specific BMD construct. The latter constraint reduced the amount of systems context below that necessary to cross this threshold.

- The Simulation Threshold--This should be crossed during Activity (3, 2), Value System Design for System Development. This properly provides simulation results and payoff values prior to heavy investment in construction. It is also the first activity in which meaningful models can be built.

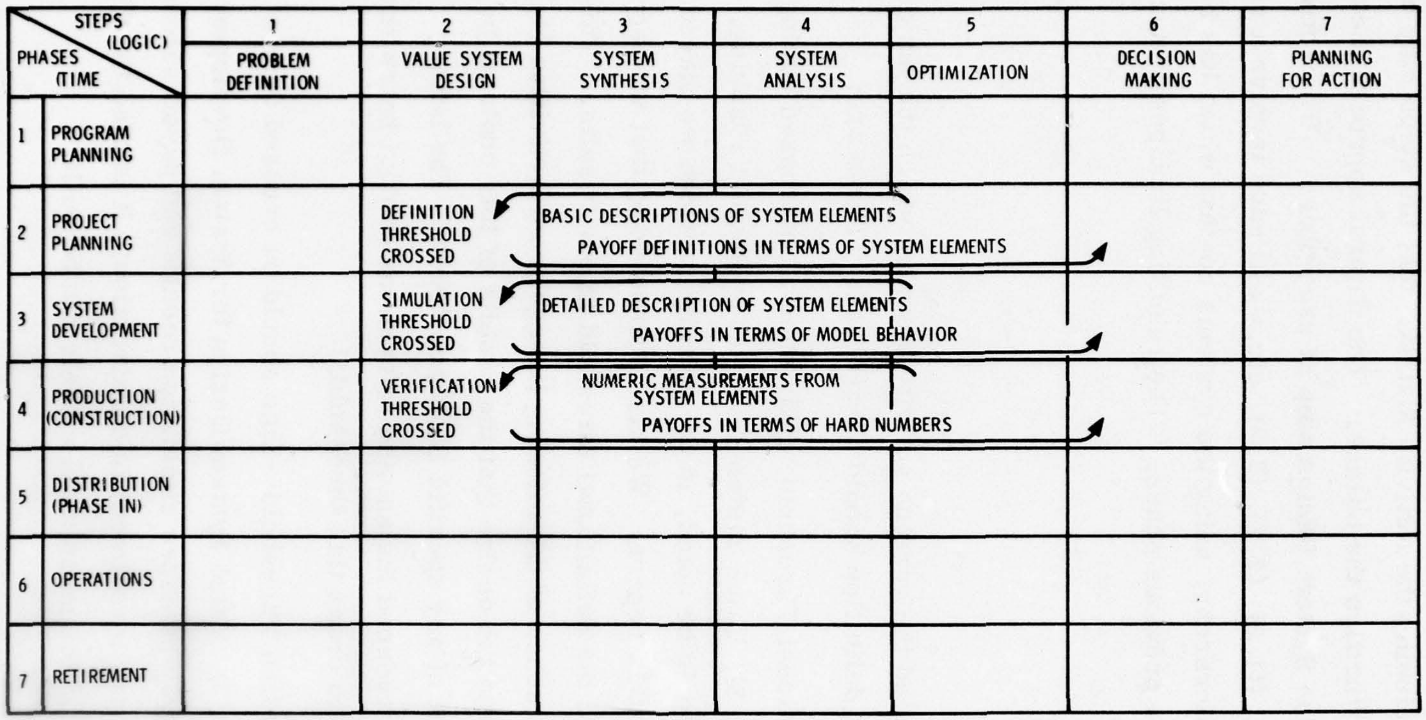


Figure 27. Linkages Implied by Natural Evolution of Payoffs

- The Verification Threshold--This can only be crossed during Activity (4, 2), Value System Design for Construction, at which time a complete and detailed systems context will be available to verify models and use in tests.

We also note that the linkages shown in Figure 27 require that activities occur in an order which is different from that implied by their numbers in the Hall Activity Matrix. All Step 2 activities (Value System Design) must take place between Step 5 (Optimize Alternatives) and Step 6 (Decision Making) in order that the systems context which resulted from a phase is used. This is not an exception to Hall's morphology since, as we mentioned earlier, the morphology imposes only a partial ordering on the activities.

Advantages

The principal advantages of the natural evolution are economy and accuracy. Payoffs are defined and evolved into quantifiable (or binary-event) form by the use of information which is developed by other activities, such as the Systems Synthesis steps. The only payoff definitions which are considered are those which are directly relevant to the system under development. Each stage in the evolution of the payoff definitions incorporates the most specific information available.

Disadvantages

The natural evolution suffers from one major disadvantage: that an adequately defined set of payoffs is not available until after committment to a specific system approach of BMD construct. This disadvantage stems from the relatively late activity (3, 2) during which the simulation threshold is crossed. As a result, the natural evolution cannot be used to derive a payoff hierarchy which will be useful during Phases 1 and 2, when BMD constructs are being selected and evaluated. This disadvantage was the motivation for developing the forced evolution approach which we describe next.

FORCED PAYOFF EVOLUTION

Overview

The forced payoff evolution takes place as a specific exercise within Activity (1, 2), Value System Design for Program Planning. It is intended to take the evolution of payoff definitions as far as possible. This end point will be just on the other side of the simulation threshold since to go any further requires actual system elements. The approach is based on an observation which we have made several times: that refined definitions of payoffs require systems context, detailed knowledge of specific system characteristics. The approach begins with a preliminary payoff hierarchy. It then defines, in an orderly fashion, a set of generic BMD constructs. Each generic construct is developed to a level of detail which permits modelling and simulation. The systems context thereby achieved is then used to produce refined BMD payoff hierarchies on a per-generic construct basis. This process is illustrated in Figure 28.

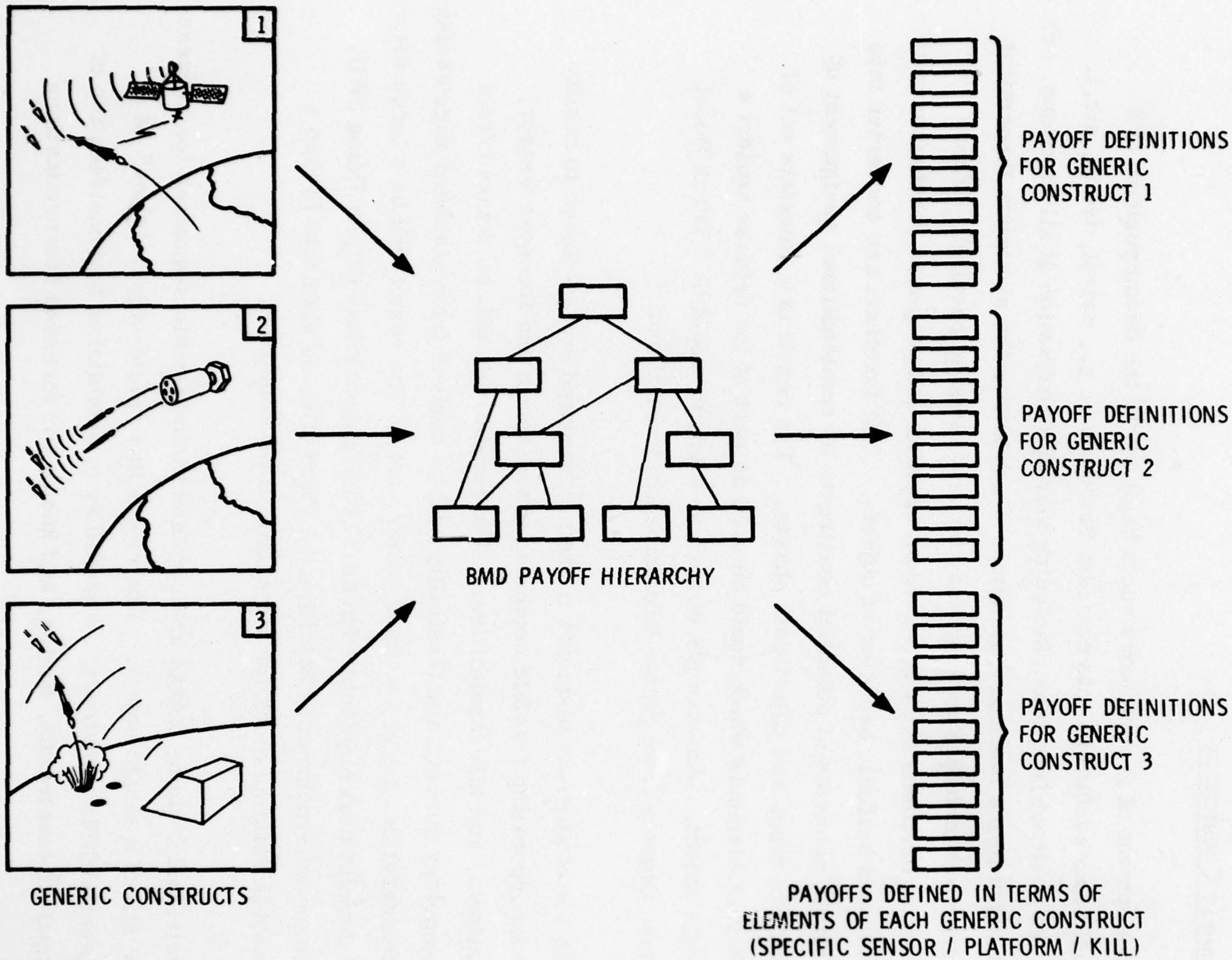


Figure 28. Forced Payoff Evolution

Generic Constructs

Development of generic constructs begins with the decomposition of a single successful kill into abstract functions (e.g., detect, track, etc.). These abstract functions, including that of coordination of all functions, are arranged into a functional structure which shows the maximum theoretical degree to which the functions may be performed in parallel. These abstract functions are derived from existing and proposed constructs and the known ballistic behavior of objects. The functions are converted into abstract elements of potential constructs by combinational assignment of platform types and object path phases. The result is a complete set of abstract elements which could be used as part of the defense against a single object. An example of such an element would be "Track Boost Phase Objects from Stable Exoatmospheric Platform."

The set of abstract elements is then refined and moved closer to reality by incorporating feasible combinations of known and foreseen sensor, platform, and kill capabilities. The capabilities will be derived from technology survey, and feasibility will be derived from standard engineering consideration of size, weight, power, etc. The result will be a large set of disjoint real elements such as "Track Boost Phase Object Using SWIR Sensor on Synchronous Satellite." Each of these elements is then a feasible building block for a potential BMD construct.

Individual building blocks are combined into feasible sequences for successful kill of a single object. The result is a single-object "slice" of a potential BMD construct. Feasibility is established by consideration of physical constraints, timing, and known and foreseen communications capabilities. Feasible "slices" are then replicated and/or combined to produce constructs. The ability of platforms to have multiple functions is taken into account at this step, along with the ability of certain platform/sensor combinations to perform functions for multiple objects.

A model is developed for each generic construct. This insures the completeness of the construct and permits exercise against various threat models. Once this is done, a BMD payoff hierarchy is produced for each generic construct. Each hierarchy will contain payoffs whose definitions are given in quantitative and binary-event terms using the elements of the generic construct.

Advantages

The principal advantage of the forced evolution is that it provides a maximum amount of information about potential BMD constructs for later activities as well as evolving a highly refined payoff hierarchy during the Program Planning Phase. Both the payoff hierarchy and the descriptions of the potential BMD constructs will therefore be available to support critical technical decision at the time that they are made.

Disadvantages

These advantages are offset by the cost of such an effort and the risk that certain feasible system elements will be overlooked or misrepresented in the generic constructs. This is an unavoidable price for early information.

SECTION 6

SUMMARY AND CONCLUSION

SUMMARY

In summary, then, we have taken the informal and intuitive concept of BMD payoffs and refined it by defining a preliminary set of payoffs and *organizing* the payoffs into a hierarchical structure. We have placed the BMD payoff effort in the context of mainstream Systems Engineering thought and indicated that the desired payoff hierarchy can be produced using the proven technique of Interpretive Structural Modelling. We showed how the resultant hierarchy can be used to compare broad technological alternatives, developed a hierarchy, and compared the alternatives of centralized and distributed data processing. We showed the close relationship that exists between the amount of detailed knowledge of a system being evaluated by payoffs and the refinement and vigor of the payoff definitions themselves. We finished our effort with two approaches which would achieve the desirable goal of quantifiable payoffs.

CONCLUSIONS

As a result of these efforts, we have drawn the following conclusions:

- Quantification of payoffs is not feasible at this time.
- The Hall-Hill-Warfield schema provides a means for comparing CDP and DDP without quantification.

- The Hall-Hill-Warfield schema also provides a useful framework in which to discuss various aspects of the BMD problem.
- The comparison of CDP and DDP which we performed, although not quantitative, showed that DDP was a better match to the BMD problem than CDP.
- The nonquantitative comparison showed that there is a definite need for quantified payoffs.
- There exist at least two approaches which will yield quantifiable payoffs.

SECTION 7

FURTHER RESEARCH

OVERVIEW

We begin this discussion by noting that our adaptation of the Hall-Hill-Warfield schema for Systems Engineering was done as a means toward the end of a comparison of CDP and DDP. We therefore only treated those aspects of the schema which directly contributed toward that end. We did, however, survey the whole field, and we are convinced that it contains many elements of potential benefit to BMD. We believe that these benefits could be realized by research in the following areas:

- Adaptation of the schema to BMD,
- Development of a preliminary BMD payoff hierarchy, and
- Forced evolution to quantifiable payoffs.

Each of these areas will be discussed in the next subsection.

RESEARCH AREAS

Adaptation of the Schema

Development and refinement of the Hall-Hill-Warfield schema has taken place in the context of urban and societal systems. This is reflected in the vertical dimension of the Hall morphology (Figure 1) which is indexed using discplines far removed from the engineering concerns of BMD. The general aspects of the schema should be preserved, new phases, steps, and disciplines should be defined, and relevant linkages should be specified. The resulting schema would provide a single context and standard set of terms for all method-related research in BMD. This in turn would provide the following advantages:

- Research plans and results would use a standard set of terms to describe the activities which were being performed or investigated. This would provide the ability to effectively compare plans and results and would show the context of research in a known format.
- Development of a linkage diagram for research efforts in a standard format would increase the chances of detecting *incomplete* efforts--those which depend on activities that have not been performed. Such a linkage diagram would prevent occurrences such as the missing linkage which plagued our effort.

Payoff Development

The need for a BMD value system is obvious. The rapid development of technology in the areas of sensors, data processing, and platforms has produced a combinatorial explosion of technological alternatives whose evaluation is extremely difficult. Any decision to develop and deploy a specific BMD system would involve a major commitment of national resources and must be guided by a detailed set of meaningful objectives.

These objectives are, in Hall's terminology, the value system and, in our terminology, the payoffs. The adaptation of the schema will specify the interrelationship between the value system and the various activities which comprise development and deployment; the payoff development will generate a specific set of payoffs which will drive interrelationships. This payoff development activity should comprise a full-scale ISM exercise. Our experience with ISM indicates that a 20 x 20 binary matrix is the largest that can be reasonably converted into a *hierarchy* by manual methods. Even then, the effort involved is a serious inhibiting factor to an iterative or trial-and-evaluation approach to hierarchy development. A number of automatable algorithms for binary matrix manipulation have been specified by Warfield [315, 316, 317, 318], and these should be implemented in order to support the use of ISM in payoff development.

The results of this research will be a preliminary set of BMD payoffs organized into a hierarchy. The vast bulk of these payoffs will be qualitative. This exercise will carry the BMD payoff hierarchy across the definitional threshold and will confer the following advantages:

- A complete description of BMD policy will be available in technologically relevant terms as a guide to evaluating technology and establishing research directions.
- A structured definition of BMD policy will be available to provide insight into the BMD problem for interested parties outside the BMD community.

Forced Evolution

The payoff hierarchy which results from the above effort can then be used as input to a full-scale exercise of Activity (1, 3), Systems Synthesis for Program Planning. This activity should proceed in the following steps:

- The forced evolution method which was described above should be refined and planned in greater detail. A specific set of functions should be derived, and sources of the known and foreseen sensor, platform, kill, and communication capability should be identified.
- The refined method should be used to generate a set of generic constructs. These constructs should be produced in order of increasing risk; that is, the first ones should use the *maximum amount of known or "in-hand" technology.*
- The most reasonable and the most promising of these generic constructs should be modelled to the level of detail that permits quantifiable or binary-event definitions of payoffs.
- A payoff hierarchy should be refined for each construct, using the primitives defined for their models.

The result will be a set of payoff hierarchies which permit comparison of detailed data processing technological alternatives. These comparisons will be quantifiable (or binary event) and will be relevant because they will take place in the context of a set of sensor, platform, kill, and communication capabilities. The data processing planning and research will therefore have available to it a real set of objectives--not "real" in the sense of attainable but "real" in the sense that the objectives are stated in the terms of the objects which the data processing subsystem must manage.

It is also possible that the set of payoff hierarchies could be used to compare generic constructs as well as to compare alternatives within a construct. The payoff hierarchy for each generic construct has the same payoffs arranged in the same structure. The difference is that the definitions of some of the payoffs are construct-dependent. It is possible that the construct-dependent definitions can be restricted to payoffs that reside at low levels in the hierarchy. If this is the case, values may be computable for higher-level payoffs, values which are construct-independent. The values for these higher-level payoffs may then be used to compare generic constructs.

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