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Three Dimensional Morphology of Systems Engineering

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Abstract—A study of the structure and form of systems engineering using the technique of morphological analysis is presented. The result is a model of the field of systems engineering that may be rich in applications. Three uses given for illustration are in taxonomy, discovery of new sets of activities, and systems science curriculum design.

I. INTRODUCTION

MORPHOLOGY refers to the study of structure and form. Morphological analysis, a term coined by Zwicky [1], means to decompose a general problem or system into its basic variables, each variable becoming a dimension on a morphological box. When the values that each variable can assume are found, a set consisting of one value of each variable defines a solution to the problem or a species of the general system. This valuable approach is essentially a search technique for piling up alternatives in a design problem [2]. In this paper the technique will be used to present a new and simple model of the field of systems engineering that may be useful in surprising ways.

II. MORPHOLOGICAL ANALYSIS

Investigation of systems engineering reveals (at least) three fundamental dimensions which are as follows.

1) The first is a time dimension which is segmented by major decision milestones. The intervals between these milestones can be called phases, and they define a coarse structure depicting a sequence of activities in the life of a project from inception to retirement.

2) The second dimension models a problem solving procedure, the steps of which may be performed in any order, but each of which must be performed no matter what the problem. These steps may be repeated in successive phases. The flow of logic, not time, is the essential feature of this dimension, and this logic comprises the fine structure of systems engineering.

3) The third dimension refers to the body of facts, models, and procedures which define a discipline, profession, or technology. A possible measure for this dimension is the degree of formal or mathematical structure. The intervals along this scale in decreasing order of formal structure might be: engineering, medicine, architecture, business, management, law, the social "sciences," and the arts.

Combining the first two dimensions produces a model of the methodology of systems engineering which at once organizes and defines the field independent of any profession. This does, of course, imply that systems engineering is not a profession, since it does not contain facts, models, technology, etc., that are unique to it. To the extent that systems science is succeeding in abstracting models, concepts, facts, etc. that apply to several fields, it is fair to characterize systems engineering as an emerging profession. Fig. 1 depicts this model, called the activity matrix because each element in the matrix is defined by a unique activity at the intersection of a phase and a step of that phase. The model encompasses a vast panorama including design, which is centered about phases 2 and 3.

Most of the two-dimensional structure has been discussed previously [3]. Therefore, these broad phases and steps will be defined only briefly. By program planning is meant conscious activity in which an organization strives to discover the kinds of activities and projects it wants to pursue into more detailed levels of planning. In the language of finance, it is portfolio design.

Project planning is distinguished from program planning by interest focused on just one project of the overall program. The terminal milestone of this phase occurs when a decision is reached to develop the best of the alternative systems disclosed during the planning or to dispose of the project in some definite way.

This or any phase can be defined in terms of the steps which comprise it. Thus problem definition, activity a_{21}, includes a study of the needs and environment, and collection and analysis of data to be used in formulating the problem. Value system design, activity a_{22}, uses these data in stating the objectives to be met and prescribing a (generally multidimensional) decision criterion against which all alternatives will be measured. System synthesis refers to all means of compiling a set of contending alternatives, whose consequences are systematically deduced during the systems analysis step. These consequences are evaluated and combined according to the rules prescribed by the value system in the decision making step, which selects the best alternative. Rational choice among alternative systems requires that each system be proportionated to meet, as best it can, the objectives comprising the value system; this is the role of optimization. In the sense that this step entails iteration of the first four steps, it should not be singled out as a separate function. However, optimization often carries out this iteration by using a model for selected aspects of the system with the express purpose of optimally

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	Steps of the Fine Structure	1	2	3	4	5	6	7
	logic → Phases of the Coarse Structure time ↓	Problem Definition	Value System Design (develop objectives & criterion)	Systems Synthesis (collect & invent alternatives)	Systems Analysis (deduce consequences of alternatives)	Optimization of each Alternative (iteration of steps 1-4 plus modeling	Decision Making (application of value system	Planning for Action (to implement next phase)
1	Program Planning	• 11	• 12				• 16	• 17
2	Project Planning (and preliminary design)	• 21						
3	System Development (implement project plan)							• 37
4	Production (or construction)				• 44			
5	Distribution (and phase in)							
6	Operations (or consumption)	• 61						
7	Retirement (and phase out)	• 71	• 72				• 76	• 77

Morphology of systems engineering and its activity matrix.

proportioning the selected aspects. It is this modeling activity which justifies singling it out as a separate step. The final step is planning for action, which includes communicating results, scheduling effort, allocating resources, determining how performance is to be measured against the plan, and designing a feedback system for controlling the ensuing action. Were we not modeling a multiphasic system, we would include implementation, i.e., starting and controlling action, as a final step. However, in this model, implementation refers to the next phase.

Thus system development means to implement the plan. It entails another cycle of steps, dealing mostly with components rather than overall alternatives. The phase ends by preparing detailed specifications, drawings, and bills of materials for the manufacturer or construction organization.

Production, in the case of a manufactured product, or construction, when the system must be produced in place, refers to all those activities needed to give physical embodiment to the wanted system. For a new building, the general contractor executes the architect's plan, using the detailed plans and specifications provided by him and his consultants. For a new product, the manufacturing engineers determine the sequence, material flow, and the floor layout required, design the tooling and test jigs, and establish quality control.

Next follows distribution and phase-in of the product to ultimate consumers. This may involve all kinds of distribution facilities, sales organizations, applications, and sales engineering. The product may have a very long life, like a power dam, or it may be consumed, like a new item of packaged food.

The operations phase overlaps the distribution and retirement phases a little or a lot, depending upon the number of systems involved and the periods used for phase-in, operation, and phase-out. In any case, operation is the reason for all forms of systems engineering. Many problems arise during this phase that are not of a design nature, such as those relating to optimum utilization, which are solved by a recycling of the seven major steps of the fine structure.

Finally, the system may be retired, or more generally, phased out over a period of time while some new system takes its place. Just as for all of the other phases, a whole row of steps applies.

Consider now that a matrix of 49 activities is formed by the coarse and fine structure dimensions.

The activities of each morphological square are unique, yet there are helpful similarities and relationships. For example, the objectives selected for a particular value system design may differ according to which phase we are in; a type of objective appropriate in program planning more than likely would be inappropriate, even irrelevant, for the retirement phase. Yet in-depth knowledge of how to design and apply value systems is useful in all phases and can lead to wisdom in tailoring a value system to a phase.

Modeling the fine structure as a linear dimension on a box overemphasizes the temporal features of the fine structure and obscures certain essential features of the systems engineering process. Both the iterative and converging features of the process are emphasized by using a simple natural system as a model (thus using the essential cybernetic viewpoint [4]): a seashell viewed as a cornucopia with reverse flow. See Fig. 2.

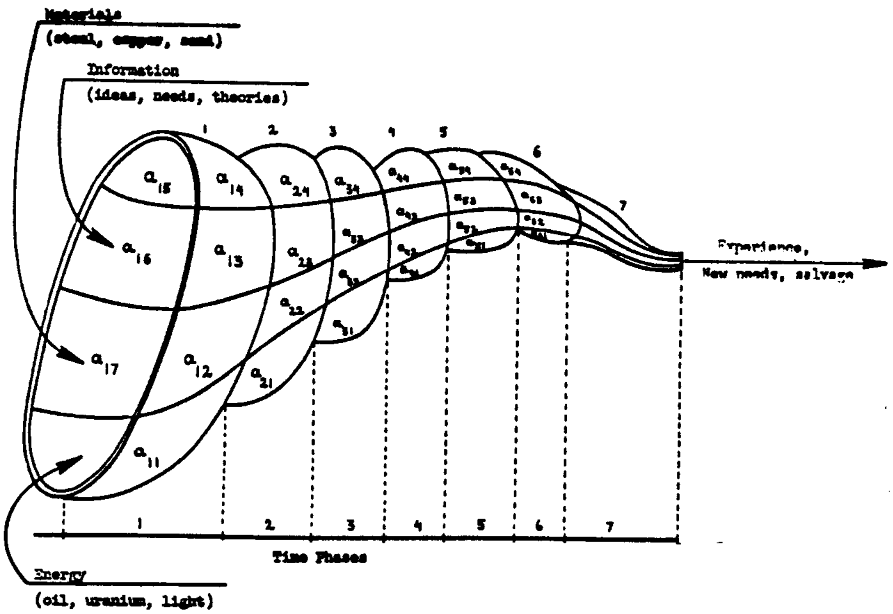


Fig. 2. Cornucopia model.

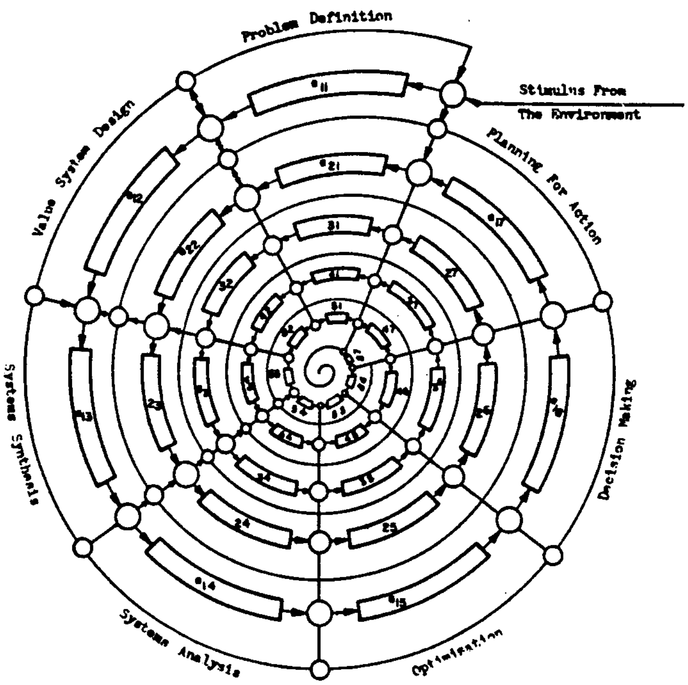
The analogy of the cornucopia to the systems engineering process is a felicitous one. The cornucopia, emblematic of abundance, was the horn of the Greek nymph Almathea which was endowed with the virtue of becoming filled with whatever its possessor wished. Here, the wishes are those of a society directing and cooperating with its systems engineers, who focus energy, information, and materials upon a successively smaller and smaller set of problems and decisions until finally a single wanted system emerges and is fit into an ecological niche. The spiraling structure converging to a point depicts exactly what happens in iterating the fine structure cycle through successive phases.

All dimensions of the spiral horn are adaptable to fit the task (as required of any good cornucopia). If we stretch the radial and transverse axes to separate the segments (taking care not to go beyond the elastic limit) and look into the larger end, we may see the hyperfine structure of this remarkable instrument. What we see is a series connection of one-way elements, providing the structural basis for forward movement, connected with two-way (feedback and feedforward) paths permitting any step to follow any other step in whatever sequence.

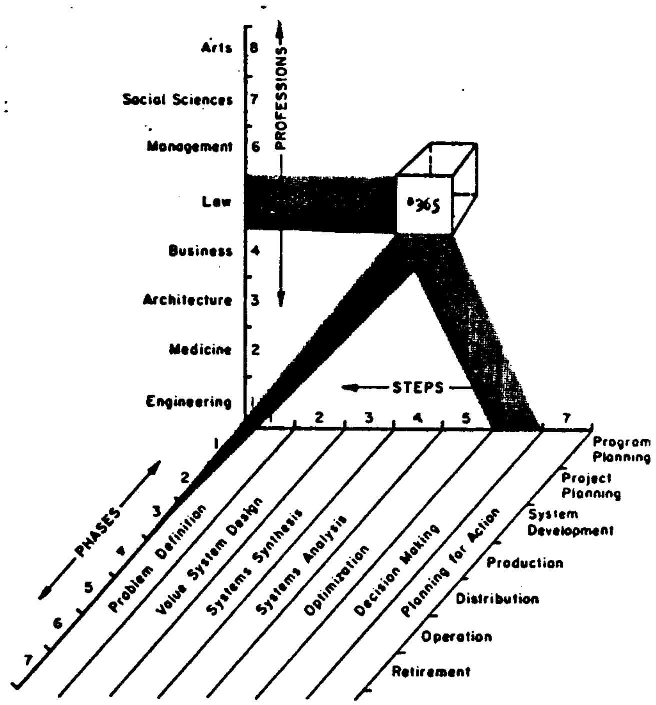
Seemingly complex beyond belief or comprehension, because we know how intractable even a single-loop feedback system can be if it is of high order and nonlinear as those are in this model, certain regularities do appear. At least, certain feedback paths appear "stronger," "more essential," or perhaps only more frequently used than others. The loop consisting of analysis, synthesis, and comparison with objectives in each phase has been singled out by some methodologists. Special emphasis has been given to this loop here also, and the loop which models value system design has been added and connected with the synthesis-analysis loop [3, Fig. 4.3]. How these two loops behave like an adaptive feedback system has been explained. Although progress has been made, Fig. 3 shows how far we would have to go to achieve complete understanding.

It must be perfectly clear that the two-dimensional morphology presented is quite different when applied to a problem in electrical communications than it is when applied to a problem in medicine or bridge construction. It follows that even if a man were perfectly versed in the tools, models, and attitudes appropriate for all of the activities on the two-dimensional morphology matrix, this would not be sufficient to produce anything really comprehensive and useful in the real world where specific knowledge and technology must be applied. The requirement for subject matter knowledge in practice should be self-evident, but, unfortunately, it is not always so. As evidence, we see consultants in operations research and industrial engineering who tend to claim that since they have grasped a universal methodology, they can produce applications in any field. Also, certain aerospace companies, claiming the systems approach, have tackled problems in transportation, education, and pollution with results that may not be what one would expect after contemplating cornucopias. Even many universities, uncritically being swept along by the tide, have established graduate curricula in systems engineering that cover a good part of the methodology, but leave the student unequipped to design anything. A few are extending the same sort of programs downward into undergraduate curricula.

Thus are we led to the third dimension, referring to subject matter fields representing what today are called professions, disciplines, or technologies. Fig. 4 defines a more well-rounded systems engineering. Within it, we may speak of more usefully defined activities such as decision making in the development phase of law (a_{365}) or the operational phase of medicine (a_{612} through a_{672}), which includes the work of the general practitioner of medicine.



Hyperfine structure.



Morphological box for systems engineering.

III. Applications

This morphological box appears to have many uses of which only three will be mentioned briefly.

A. *Taxonomic Uses*

As illustrated previously, it is possible to define well-known fields by reference to a set of compartments in the box. Attempts to do this lead to some problems caused by misnamed fields. As an example, consider the field known as "systems analysis," which was started at the RAND Corporation and continued by a rather broad group of mathematicians and economists who, among many other things, performed military "cost-effectiveness" studies. The box defines systems analysis as a deductive step only, occurring in all phases of all disciplines; this captures only part of systems analysis and credits it with working in fields where it is not found in fact. A better match occurs if we classify it as a part of the field of operations research.

Operations research started through interest in the operations phase, but it greatly expanded by using the steps in the fine structure to solve problems in other phases as well. It has spread over most of the "zero plane" of the box and has found applications in common activities in other "layers" of the box, notably, business, management, and medicine. However, in the sense that it does not use "research methodology," meaning the scientific method as used in pure science, it too is misnamed. Its methodology seeks a normative or prescriptive body of knowledge, unlike pure science which seeks "to know," and does not seek "what ought to be." The same applies to the "science" of management science. Ansoff and Brandenberg [5] think that the right solution to this little taxonomic problem is to call it "management engineering." By the same arguments, operations research should become "operations engineering," and "systems science" should become "systems engineering." Thus a broad viewpoint contributed by the morphological box can help to improve tangled terminology.

B. *Aids to Discovering, or Seeing More Clearly, Unique Activities*

One of the distinct merits of morphological analysis is that it helps to find more solutions than could be found merely by listing them. In this case, the box identifies $7\times7\times8=392$ activities, and this number can readily be increased by anyone adding professions and subdividing phases and steps, according to his own viewpoint. The importance of this is that the delineation of many unique activities by the combination of variables invites a large number of new questions. (Any good research raises more questions than it answers). One class of such questions is about the existence of a given combination. Many inventions have taken place by elaborating a combination which at first seemed foolish or farfetched. This class of questions will be exemplified.

Is each layer of the box really complete all over the plane? In other words, does each profession really have a methodology as well developed as "conventional" systems engineering from which the box was derived? It is, of course, not too difficult to imagine problems in law, the arts, etc. and "force fit" the methodology of the first layer to them, but this proves nothing, except perhaps our ingenuity.

There is very little evidence to suggest that a "medical systems methodology" or a "legal systems methodology" has been worked out. Nadler [6] reports interviews with an engineer, a lawyer, a commercial artist, a physician, and an architect about the procedure each followed in a recent specific design project. These were the results:

> The research group concluded that there were strong similarities in steps used by those interviewed. Although there was not enough evidence to support a conclusion that the design approaches of various professions could be translated into one design model, such an assumption seemed justified as a working hypothesis.

Even if the hypothesis were validated (the author's own experiences both in engineering and nonengineering areas lend support), it is a far cry from here to well-reasoned and formulated methodologies which have consensus within the various professions.

Yet what a boon it would be if a common methodology were developed for the professions! Agreement merely upon common names for phases, steps, and structural elements alone would assist greatly in the transfer of knowledge among the professions. The potent idea of the "portable concept" given by Linvill [7] would begin to realize its potential. The "two-culture problem" discussed so much by Snow [9] is most acute between pairs of professions farthest apart on the "professions" scale of Fig. 4, precisely because of the most diverse methodologies and subject matters. Yet the author's experience is that people "farthest away" from engineering, such as in the "social sciences," have the greatest expectations that somehow engineering can give a great infusion of models, methodology, and techniques.

None of this should be interpreted to mean that engineering methodology is in such fine shape as to be a fit exporter. While being able to pinpoint its weaknesses, the existence of a tenable and useful methodology for engineering (including, at least, systems engineering, management engineering, and operations engineering) seems beyond question, despite the more fainthearted proposition by Zwicky in [8] that one might now be attempted. There are, of course, plenty of scientists and a few engineers who gainsay all of this and who either hold to a purely heuristic method or fear that the evolution of a better methodology will lead to blind rule following. Both views are silly, and it would be illuminating to prod such people into print.

C. Aid in Curriculum Design

A final use for morphological analysis is in the design of academic curricula. In many new graduate school curricula in systems engineering, it is good to see emphasis on probability, statistics, mathematical optimization, statistical decision theory, etc. These tools are all useful and none should be banished. It is important, however, that these subjects be seen largely as the tools for the systems analysis step, which is only one of seven to be played together as an organ. The morphology suggests that there is no logical priority among the steps of a given phase; none of them is more important than the others. It follows that a unified curriculum requires some balance of emphasis upon each step in at least one phase of at least one profession. Schools which stress design courses achieve a better balance across the steps, but they give little balance across the phases since design centers about phases two and three.

The morphological box, of course, suggests tremendous challenges to curriculum designers to develop systems science and systems engineering which will permit one to operate effectively in several professions at once. Meeting these challenges calls for further weakening of the ossified partitions that separate the professions in most universities. False value systems, which tend to prevent research and teaching in fields that may not now be mathematizable, must also go. (Whoever heard of a course on problem definition?) In business, the rigid barriers between sales and marketing, research and development, manufacturing, finance, etc., are just as confining as those in the universities. And the unnatural wall between the mandarin society of the university and the pragmatic society of business serves neither in the evolution of systems curricula.

IV. CONCLUSION

We have to be modest even with perfect knowledge of a two-dimensional coarse and fine structure. But it is essential to see it whole to acquire a deep grasp of the process and facility with each of the activities of the process because it does, in fact, portray the essence of the systems approach. And this wholeness does aid in acquiring and using knowledge of disciplines comprising the third dimension.

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