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ABSTRACT

This paper describes ideas initiated as a step toward reaching a better understanding of the design process, the factors affecting engineering design, and how the engineering design process might be beneficially influenced. The starting point for the effort was a consideration of: (1) the recent historical development of Systems Engineering, and (2) the uniqueness of Systems Engineering. The idea of trade studies is emphasized as part of the Design Process. The skills and capabilities necessary for such are enumerated and described. A survey summarizes the engineering curriculum requirements of 70 programs at 20 universities. It was shown that trade studies are consciously or intuitively used at all levels and in all fields of engineering. The uniqueness of Systems Engineering is stated to be based on methodology rather than science, industrial need, or devices. A proposed non-credit course is briefly described. (EB)

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Trade Studies, an Important Component of Systems Engineering

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TRADE STUDIES, AN IMPORTANT COMPONENT OF SYSTEMS ENGINEERING

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The thoughts reported below were initiated as a step toward reaching a better understanding of the design process, the factors affecting engineering design, and how the engineering design process might be beneficially influenced. It appears probable that engineering education is one of the stronger factors determining how an engineer goes at his work. The educational process appeared to be a logical area to look into. The starting point for this effort was a consideration of:

1. The recent historical development of Systems Engineering.
2. The uniqueness of Systems Engineering.

Recent Historical Development

The word "recent" was inserted purposefully. Examples can be found where the systems approach to engineering problems has been used in the more distant past, but the recognition and identification of Systems Engineering as a separate discipline has been a fairly recent development. During this development, there were many who insisted that Systems Engineering was merely "good engineering," not something different or unique.

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One of the characteristics of the approach to engineering which came to be known as Systems Engineering was the consideration of the problem in its entirety, clearly defining the objectives, restraints, and interactions. In "good engineering," this was always the intent, often done by the project engineer, and often in an informal or intuitive way. The process included a high degree of common sense and experiential judgment. The availability of computers allowed this procedure to be carried out more rigorously and formally.

A second characteristic noted in the recent historical development of Systems Engineering is the conscious and large scale application of "trade-offs" (or trade studies). Trade studies are claimed by many to be synonomous with engineering. Trade-offs are made consciously or subconsciously at all levels of engineering, from material selecting and component design to the decisions on the basic methods to be used to reach an objective.

In the not-too-distant past, the engineer was limited in his use of trade studies by his ability to calculate and analyse the trades involved and by the time constraint. Too frequent and extended trade studies were sometimes looked upon (and sometimes became) means of delaying or avoiding the making of critical decisions. Again, the availability of computers made extensive trade studies feasible, and legitimatized this approach. At one point in its development, the formal application of trade studies was looked upon as a key feature of Systems Engineering.

An example of trade studies being identified with Systems Engineering is contained in AFSCM 375-5 (10 March 1966) Exhibit 1, Procedures for Systems Engineering Management. This document, now superseded, details the procedures through four project phases (Conceptual, Definition, Acquisition, and Operational) by means of a flow chart containing 106 blocks. Seven of these blocks specifically call for trade-studies, e.g.,

Block 8. Identify and Perform Trade-Off Studies

Block 16. Perform Selected Trade-Off Studies and Identify Definition Trade-Off Requirements

Block 44. Perform Trade-Off Studies (Operations Design vs Maintenance Design)

In the instructions describing each block in the procedure, there are many other references to performing of trade studies, reporting of trade studies, using trade studies to support decisions, etc. Trade studies appear to be a key element in Systems Engineering by the Air Force.

Educational programs in Systems Engineering developed along several directions. Three of the directions initial efforts took are Systems Theory, Systems Dynamics, and Systems Engineering developed along interdisciplinary project lines. This last approach is broader, more comprehensive than the most others. It is exemplified by the work of Bollay at MIT and Stanford.* In his reporting on this project

*William Bollay, "University Projects in Systems Engineering," Engineering Education, Vol. 60, No. 8, pp. 803-5 (April 1970).

approach, Bollay emphasizes the need for innovation and for the evaluation of alternative approaches, the iterative nature of the design process, the need to account for interactions between elements in the design of each element, and the interdisciplinary nature of Systems Engineering design. While not mentioned specifically, trade-offs was an essential ingredient to his design process.

Thus, in the early and mid 1960's, trade studies emerged as an identifying feature of Systems Engineering. Recently trade studies have received less emphasis as Systems Engineers have devoted their time to more sophisticated topics such as input-output analysis and systems identification. However, when it comes down to getting something designed, built, and operating, trade studies can still be a key and useful procedure.

Uniqueness of Systems Engineering

There are many definitions and many descriptions of Systems Engineering. The definition (if it is such) being developed here is not claimed as being inclusive, definitive, and/or final; it is developed to provide insight into the nature of the engineering process and how it might be influenced.

Many claims are made of Systems Engineering. Some are applicable to many fields of engineering, e.g., describing it as an input-output problem involving the definition and design of a system to satisfy the requirements is not unique; this approach can be applied to a control problem, an industrial engineering problem, etc.

A unique characteristic of Systems Engineering is that it developed from a methodology (or a number of methodologies). Being based on methodology, it differs from other fields which are based on particular fields of science (Electrical Engineering, Mechanical Engineering), on industrial activities (Sanitary Engineering, Petroleum Engineering), on materials (Ceramic Engineering), or on devices (Automotive Engineering).

The methodologies of Systems Engineering incorporate a number of concepts, some of which are closely or primarily identified with Systems Engineering. These are:

1. Unitary Concept. Solving the problem as a whole.
2. Trade Studies. Consciously and extensively used.
3. Portable Concepts. Use of analogies, commonality and generalities in science; cross discipline methods.

To these might be added concepts important to Systems Engineering which are not necessarily unique to this field.

4. Wide use of
   - a) Input-output analysis
   - b) Feedback
   - c) Modeling
   - d) Simulation
   - e) Use of computers

These characteristics have been diagramed in Figure 1. Here, "The Design Process" appears as a large blank. The next step is to fill in this blank.

The Design Process

The unitary concept in Systems Engineering depends on everything that goes on within engineering. It is an identifying characteristic but not an operational one; its application depends on application of the other factors.

The portable concepts provide additional tools which makes cross-discipline approaches feasible. This area is well covered in texts and in engineering courses.

Trade studies remain as historically a key concept in Systems Engineering, and in the present as a procedure unique to Systems Engineering in the degree to which they are used. However, the method does not appear to receive the attention it may deserve in the engineering education process. Examining the indexes of design texts and Systems Engineering texts will reveal very few references to trade-offs or trade studies. Like "engineering design," or "the engineering method," trade studies appear to be taken for granted, something everyone assumes everyone knows.

Trade Studies

Trade studies might be broken down into three elements, or steps:

1. Generation of alternatives.
2. Assigning of values to the characteristics of the alternatives.
3. Making a decision; choosing the "best" or the optimum.

These three steps have been filled into the Design Process box of Figure 1, to produce Figure 2.

Figure 3, an elaboration of Figure 2, shows how the components of Figure 2 relate to the engineering profession and the engineering process.

Figure 4 is a further elaboration of Figure 2. While Figure 2 shows the development, evaluation, and choice of alternatives to be the central feature of the engineering design process, Figure 4 shows that within each design there are subsystems which can be subjected to the same process; further, in each subsystem there is the design of components which can also be subjected to the trade study approach. Note that each component and each subassembly may interact with each of the other components or subassemblies. Each may be affected by or may affect the others. It is at this point that engineering experience and judgment, the result of practice, is important in deciding how many alternatives to evaluate and what interactions are significant.

The three steps of the trade study requires certain skills and capabilities. Some of these are:

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Step	Skill
1. Generation of alternatives	1. Creativity; innovation; engineering capability (tools, methods, practice)
2. Value assignment; criteria selection and weighting	2. Value systems; value clarification; objective formulation
3. Choosing the "best" or optimum	3. Optimization techniques; decision theory

Among the skills required, the engineering capability can be presumed. This is the area in which engineering schools place most of their effort.

To verify the results of our personal observations and experience regarding the other skills, a small survey was made by checking the catalogs of 20 universities. The results, shown in Table 1, confirm our original impressions. The programs surveyed covered largely the traditional disciplines. Only 3 of the 70 programs were Systems Engineering.

TABLE 1

Engineering Curriculum Requirements

(A Mini-Survey)

70 Programs in Engineering at 20 Universities

	Elective Courses	Required Courses
Creativity	1	1
Value*	0	0
Decision Theory and Optimization	21	8

*Does not include Liberal Arts and Humanities, required or elective. (See discussion in text.)

Decision Theory and Optimization are taught quite widely, being required in 11% of the programs and available in an additional 30%. Recognizing that it is impossible to put all desirable topics into a single four-year curriculum, we might conclude that these subjects are available to many who might benefit from them.

Creativity, as a separate subject, appeared in only 3% (2 cases, one required and one elective, out of 70 total) of the programs. While creativity appears as a chapter in several different engineering texts, and sometimes appears as a lecture or a week's study in engineering courses, we might well ask whether students would not benefit from a greater exposure. Certainly being creative or innovative is an important capability for engineers to possess.

No program showed a course that could be interpreted as dealing directly with values. While humanities and cultural type courses provide a background against which values may develop, they rarely relate the need for values and the application of values to the professional work of the engineer.

Values cover a broad spectrum. One categorization might be:

1. Sociological. Cultural, social, political, economic, religious.
2. Human Factors. Operability, reliability, maintainability, repairability (the - ilities).
3. Technical Factors. Performance, weight, cost, etc.; common basis for comparisons; life cycle costs.

Some of these topics come under Value Engineering, a specialized field. Courses are not generally available to most engineering students. Many of the topics are covered, or mentioned, in various engineering courses,** but the coverage does not match the importance in engineering work.

The topics listed under "sociological" are taught in separate courses or several separate courses in Liberal Arts Colleges. These topics are rarely taught as factors contributing to the formulation of value systems, and still more rarely are they taught in relation to engineering design.

There have been a few courses developed to involve engineering and non-engineering students. These are usually courses in Technology and Society, courses in environmental problems, etc. Their purposes are often to lead the student to discover how individuals from various disciplines can contribute to his problems, and how engineering methodologies may be applied to problems of interest to society. While values may be a part of the course, the generation and evaluation of values is generally not a primary objective.

**1975 ASEE Annual Conference, Colorado State University, Event 3550, "Report on Engineering Design Education Project Survey," Jankowski, et. al.

Engineering Design

Design is a primary function of engineering. While the substance of this report evolved from a consideration of the design process in Systems Engineering, most of the results are applicable to all fields of engineering. In the Figures (all) if block 3 representing the idea of Portable Concepts and the dash line which creates block 1 (leaving the contents of block 1) [illegible] removed, the remainder of each Figure is a reasonable representation of the engineering design process. It will apply to any field of engineering.

The conclusions regarding trade studies, their elements, and the teaching of the required skills are also applicable to engineering design in all fields.

Summary and Conclusions

Trade-offs (or trade studies) are consciously or intuitively used at all levels and in all fields of engineering. Their wide-spread formal use was an important characteristic of Systems Engineering in its formative stages.

The uniqueness of Systems Engineering is that it is based on methodology rather than science, industrial need, or devices. Concepts important to the methodology include the unitary approach, use of trade studies, and the so-called portable concepts. Of these, trade studies receives the least emphasis in engineering education.

Trade studies require generation of alternatives, assignment of values, and a process for making a decision. Skills required in addition to the technical capability for engineering include creativity, generation of value systems and value weighting, and knowledge of optimization techniques and decision theory. In engineering education, creativity receives some attention, value systems almost none. These are areas where engineering students might be given better preparation.

The discussion and results regarding trade studies are also applicable to engineering design in other fields.

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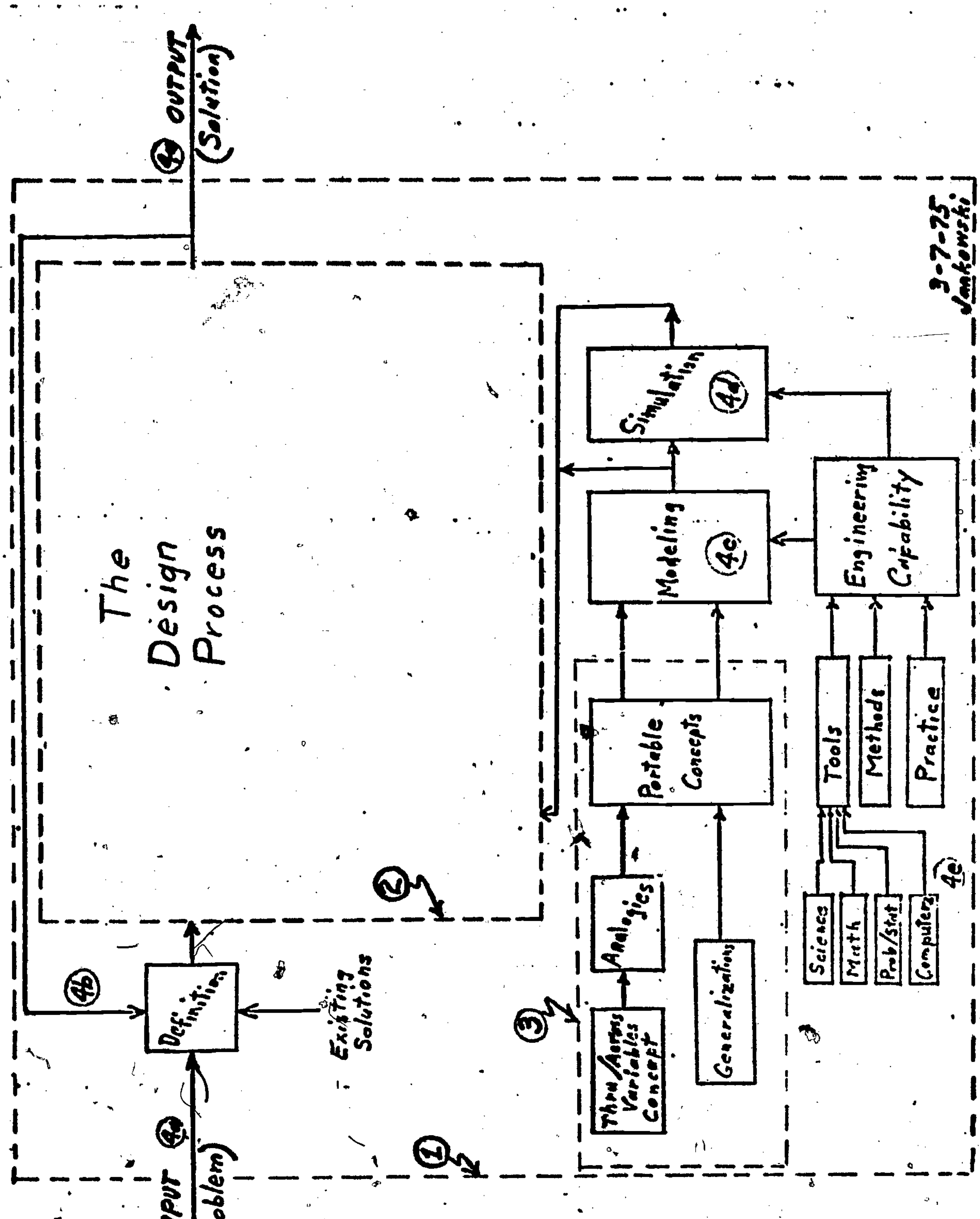
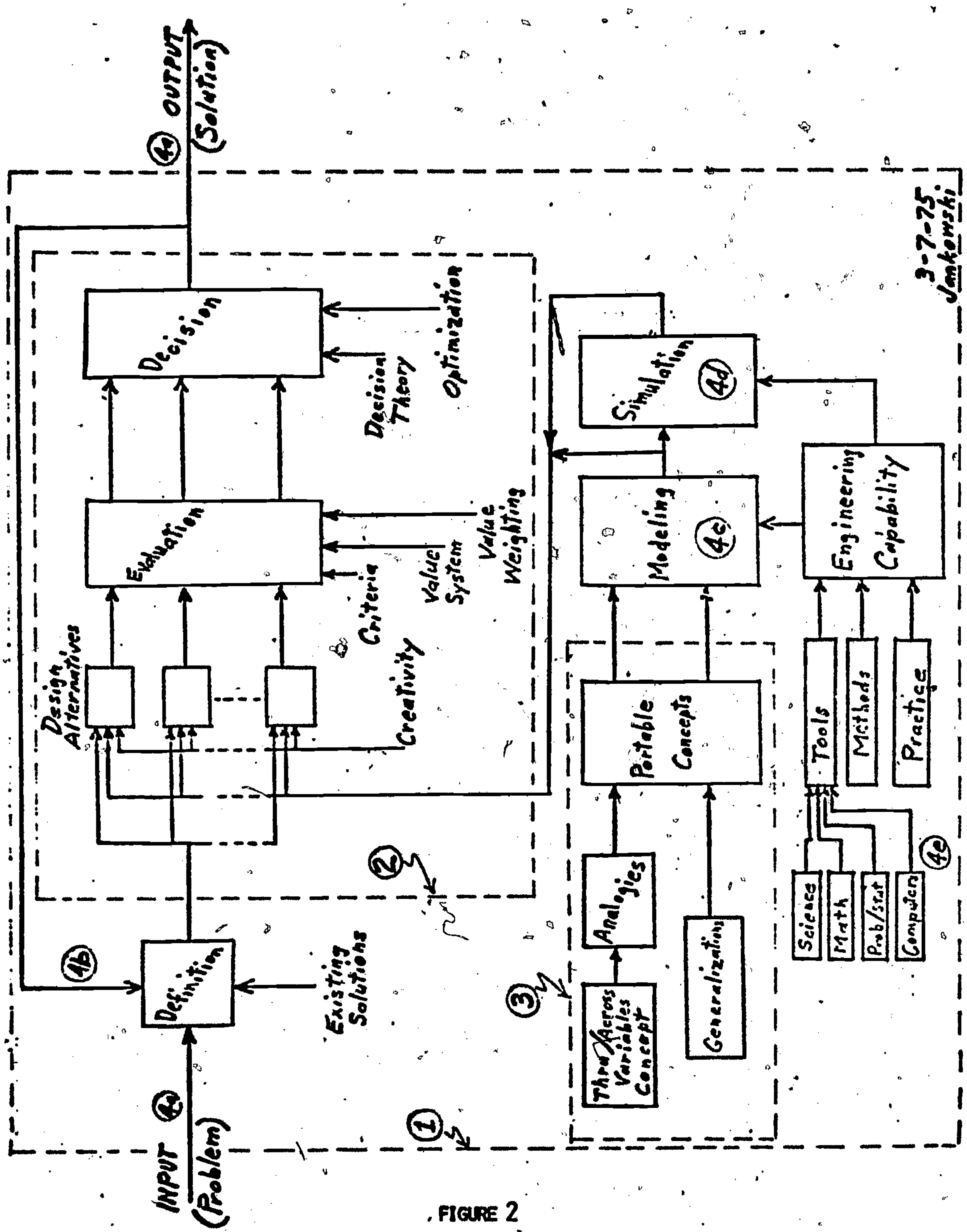

INPUT (Problem) 4a
Definition
Existing Solutions
4b
The Design Process
2
1
OUTPUT (Solution) 4a
Simulation 4d
Modeling 4c
Engineering Capability
Portable Concepts
Analogies
Generalizations
Thru/Across Variables Concept
3
Tools
Methods
Practice
Science
Math
Prob/Stat
Computers
4e
3-7-75

FIGURE 1



INPUT
(Problem)
4a
OUTPUT
(Solution)
4a
Definition
Existing Solutions
4b
Design Alternatives
Creativity
Evaluation
Criteria
Value System
Value Weighting
Decision
Decision Theory
Optimization
1
2
3
Three Across Variables Concept
Analogies
Generalizations
Portable Concepts
Modeling
4c
Simulation
4d
Engineering Capability
Tools
Methods
Practice
Science
Math
Prob/stat
Computers
4e
3-7-75
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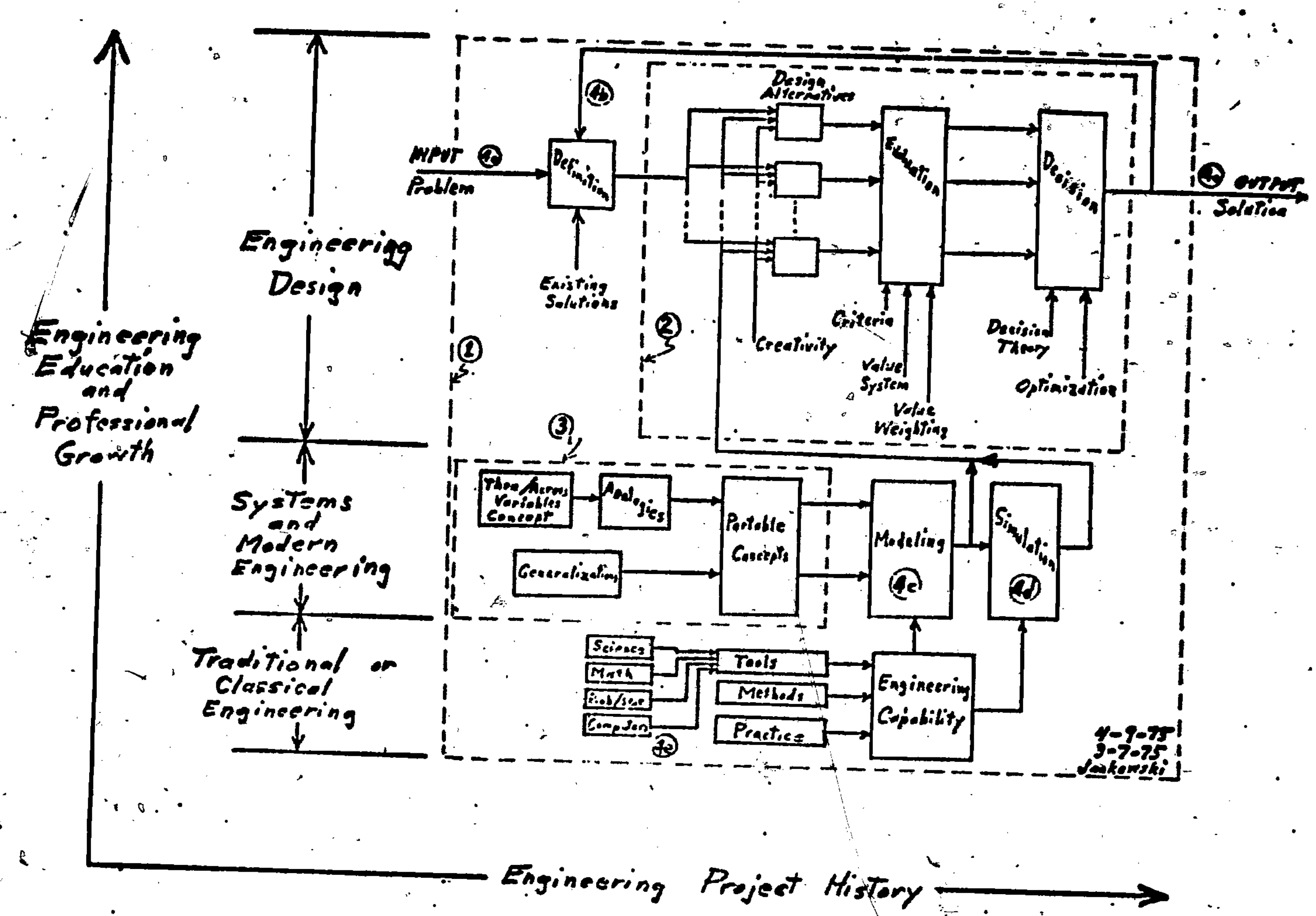
FIGURE 2



Engineering Education and Professional Growth
Engineering Design
Systems and Modern Engineering
Traditional or Classical Engineering
Engineering Project History
INPUT
Problem
Definition
Existing Solutions
Design Alternatives
Evaluation
Decision
OUTPUT
Solution
Creativity
Criteria
Value System
Value Weighting
Decision Theory
Optimization
Three Across Variables Concept
Analogies
Generalization
Portable Concepts
Modeling
Simulation
Sciences
Math
Tools
Methods
Practice
Engineering Capability
4-9-75
3-7-75

FIGURE 3

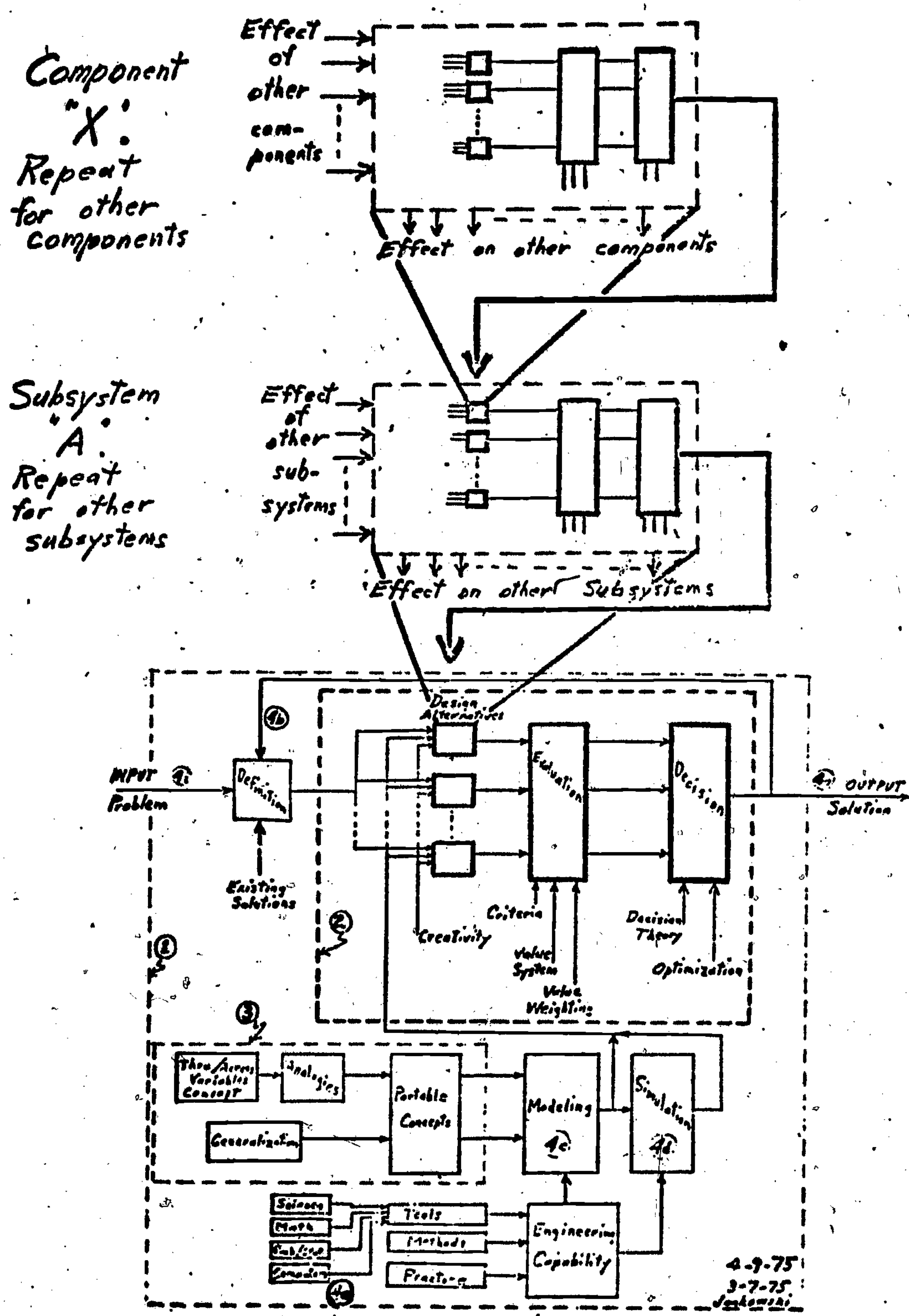

Component "X": Repeat for other components
Effect of other components
Effect on other components
Subsystem "A": Repeat for other subsystems
Effect of other sub-systems
Effect on other Subsystems
Design Alternatives
INPUT Problem
Definition
Existing Solutions
Evaluation
Decision
OUTPUT Solution
Creativity
Criteria
Value System
Value Weighting
Decision Theory
Optimization
Analogies
Portable Concepts
Generalization
Modeling
Simulation
Science
Math
Tools
Methods
Practice
Engineering Capability
4-9-75
3-7-75

FIGURE 4

NON-CREDIT COURSE PROPOSAL

to

ENGINEERING and SCIENCE INSTITUTE of DAYTON

The Compleat Engineering Manager

or

The Trade-Study Approach to Engineering Design

A course for engineers newly promoted to management, engineers contemplating entering management, and design engineers.

Engineering design requires decisions which involve many factors other than technical. This course will introduce several topics which engineers often treat lightly: the process of creativity and innovation; value systems including social, economic, the ilities (operability, maintainability, reliability), human resources, and technical factors; optimization and the decision making process.

The objective is to develop a capability for doing more "complete" designs to meet the needs and the competition in today's environment.

Dr. Jankowski will be the course coordinator and one of the lecturers. Others will present materials on creativity, values, decision making and other topics.

Tentative course outline:

10 weeks, one 2-hour class per week

I. A. Introduction. Phases of design; nature and place of trade-studies

B. Basic engineering principles: conservation and continutiy laws; node-loop approaches.

II. Basic engineering principles: across/through variables; dynamic analysis; modeling.

III. Creativity - individual: potential; techniques.

IV. Creativity - environmental factors: organization and physical factors; "technical gate-keepers"; pinnacles of excellence.

V. Value systems: cultural, social, political.

VI. Value systems: human factors, reliability, maintainability, operability

VII. Value systems: technical factors; common bases for comparisons; life cycle cost.

VIII. Optimization techniques: linear and dynamic programming; search techmiques.

IX. Decision theory

X. Summary and application