Needs, Opportunities, and Options for
Large Scale Systems Research

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by

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The Office of Energy Research was recently asked to perform a study of Large Scale Systems in order to facilitate the development of a true large systems theory. It was decided to ask experts in the fields of electrical engineering, chemical engineering and manufacturing/operations research for their ideas concerning large scale systems research. The author was asked to distribute a questionnaire among these experts to find out their opinions concerning recent accomplishments and future research directions in large scale systems research. He was also requested to convene a conference which included three experts in each area as panel members to discuss the general area of large scale systems research. The conference was held on March 26-27, 1984 in Pittsburgh with nine panel members, and 15 other attendees. The present report is a summary of the ideas presented and the recommendations proposed by the attendees.

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Chapter 1
Research Directions for Large Scale Systems

The primary purpose of the 1984 Conference on Large Scale Systems Research was to determine several high-risk, long-range research areas which, if successfully pursued, would have significant impact on the design and operation of future systems and the redesign and operation of current systems.

One of the things that became evident in the conference was that the arbitrary division of the study of systems into separate parts such as, system modelling, mathematical solution, computer solution, and managerial implementation is not necessarily productive because each part has a significant interaction with each other part. Some researchers can, will, and should concentrate on narrowly-focused technical problems in a single area. But in order to create feedback loops connecting the various areas, other kinds of more global research, perhaps done by research teams, which combine expertise from several areas is also needed. When possible such teams should include members from academic and industrial organizations, and/or governmental laboratories.

In Section 1.1 the principal recommendations of the panel members are listed with justifications and estimates of time needed and costs. Section 1.2 gives an analysis of the questionnaire responses received from 20 respondees.

Chapters 2-4 give background information which will help in the understanding of the recommendations given here. The complete questionnaire results are given in the Appendix.
1.1. Major Research Recommendations

The principal recommendations for near and long term research are collected in the following list. Explanation and justification of each of the recommendations in specific areas is given in Chapters 2-4. In the research recommendations below no mention of specific application areas is given since problems of the types mentioned can (with a few exceptions) be found in each of the three main areas covered in this report.

The time estimates for near and long term research are approximately as follows:

- For near term research topics: 5 to 10 person-years, but completed in 2 or 3 years.
- For long term research topics: 10 to 15 (or more) person-years, but completed in 5 to 10 years.

The estimated costs of each kind of project can be obtained by multiplying the number of person years by the current average yearly cost of a researcher, which should include summer support, a graduate student, supplies, computer time, travel and overhead.

The research topics for Large Scale Systems (LSS) are listed in approximate order of priority. The recommendations are not broken up into research proposal units, but are usually in much bigger chunks. Also the solution of one of these problems in one of the specific areas should, at the very least, be a good starting point for the solution of a similar problem in another area. Perhaps some of the communication links between the various disciplines that were set up at the conference can be maintained in the future.

Super Computers and Parallel Computation for LSS

The first generation of super computers was produced in the early 1970's. For lack of funds, no university in the United States was able to purchase one, although several were made available to European Universities. Only a few United States firms purchased these computers. Therefore there is very little experience reported with such large and fast computers. Currently at least three groups, one in Japan and two others in the US, are developing such computers, and it is imperative that large Universities, consortia of large and small Universities, or consortia of Universities and Industries obtain super computers and begin to experiment with their usage even though they will cost at least eight million dollars each. There is no other single project which is likely to make a larger impact on LSS research than this one.
Advances in the use of super computers will help industrial research, development and application. It will be possible to improve control of large scale systems with improved efficiency, safety, and reliability. Also academic research will be improved because larger problems, and new kinds of problems will now be amenable to research whereas they were not before.

**Near Term Research:** increasing the scale size of current models; experimenting with parallel computing steps in the current solution procedures; improving the accuracy of current computations; trying larger monte carlo and simulation runs on current models.

**Long Term Research:** develop genuinely parallel models and using parallel solution techniques on them; develop parallel simulation models; develop parallel algorithmic techniques; develop real time models.

**Deterministic Control and Operation of LSS**

More and more large scale systems are under construction or have been built. The problem of controlling them is therefore becoming more and more important. Examples are the control of large nuclear and coal fired power systems, power grid systems, large chemical processes, space systems, communication networks, etc. Research results in the area of deterministic control of such systems will benefit the owners, operators, and equipment manufacturers for such systems.

**Near Term Research:** dynamic state estimation techniques; demand forecasting; demand profile control; performance indices; startup and shutdown procedures.

**Long Term Research:** structural design; layout problems; assignment problems (customers to warehouses; warehouses to factories); location problems; expert systems design.

**Stochastic Control and Operation of LSS**

Realistic control problems inevitably involve uncertainties of various kinds. Thus such elements must be added to the models of the preceding recommendation and an evaluation of their importance made to see whether modifications need to be made to the control rules previously developed. As a general rule of thumb when there are uncertainties, additional "safety" factors must be employed. The beneficiaries of this research are the same as those mentioned in the previous recommendation.

**Near Term Research:** sensitivity and robustness to parameter uncertainties; dynamic state estimation techniques; performance oriented adaptive strategies; protection against future uncertainties.
Long Term Research: decentralized stochastic control; long term global dynamic models; expert systems for control; distributed estimation and control; demand forecasting; raw materials forecasting; hedging strategies against future uncertainties.

Optimal Design and Synthesis of LSS

This topic was emphasized by the chemical engineers for whom the problem is most pressing. As indicated in Chapter 4, the sizes of the models that they face are enormous and advances are needed to make possible design improvements in the chemical engineering and the other two areas. Essentially every area covered in this report will benefit from research in this area. Also the United States economy will be able to withstand the pressures of international competition if it is able to design better, more efficient plants than those which are in existence or which are currently being designed. The more efficient plants can economically be built in this country instead of abroad.

Near Term Research: flow sheet modelling and solution; economic analysis of projects; layout and location problems; decomposition techniques (hierarchical design and solution); integrated control and maintenance.

Long Term Research: designing best strategies when faced with uncertain forecasts of future demands; availabilities of future raw materials, supplies and prices; uncertainties concerning future technologies and forecasting of future competition and long term economic factors.

Artificial Intelligence and Decision Support Systems for LSS

Nearly every speaker in the conference mentioned the importance of expert systems, artificial intelligence, and decision support systems to each of the areas. The reasons for the importance of these areas are that large scale systems are becoming more and more complicated, and it is difficult to train people adequately to operate them. Also numerous activities are being carried out in hostile environments, such as on ocean bottoms, in outer space, in radioactive environments, in mines, etc., and it is desirable to have intelligent (non-human) operators to work in such environments. The designers and operators of such large scale systems will be the major beneficiaries of such research, but it is to be expected that there will be a number of spin-offs of this research which will result in the formation of entirely new industries.

Near Term Research: in each area the following should be constructed: large data bases; large inference "machines"; engineering work stations; CAD tools.
**Long Term Research:** Develop programs that can solve "goal directed problems" such as, "Solve the startup problem," or "Develop a good scheduling algorithm"; develop natural language programs that can accept verbal commands; work on artificial sensing hardware and software for robots and "smart" machines.

**Data Base Management for LSS**

The optimal design of many large scale systems involves the computation by subroutines of models of physical or chemical processes. Since the physics or chemistry of such processes is well known it seems desirable to put a model of the process on a chip so that it can be integrated into the hardware of the computer being used to solve the problem. In this way the speed of computation could be increased and the development of large scale models speeded up. Another problem is the coordination of several different data bases needed to carry out design problems. Since the units, accuracy, word length, etc., of each data base can be (and frequently are) different, management of the data base is difficult. Good methods for data base management would be beneficial to designers, manufacturers, and users of large scale equipment.

**Near Term Research:** chemistry on a chip; physics on a chip; development of relational data base management techniques; data base machines; graphics engines.

**Long Term Research:** maintain dynamic data relationships; data coherence and consistency; distributed data base management.

**Multi-Modelling and Control of LSS**

Since large scale systems are operated by a number of different people who are dispersed geographically, and who frequently belong to different organizations it has been found that very often each person or agent in the system develops his own "model" of it. Naturally these models differ considerably, and in particular the objective functions of each of the agents can be quite different. As a result the behavior of the system may be quite different from that which was planned. The fact that an agent's behavior in a system can be affected by his own personal model of the system must be taken into account in devising optimal control procedures. Considerable research is needed to determine the best way to do this. Advances in the solution of this problem will be of use to the managers of large scale systems.

**Near Term Research:** develop multi-modelling techniques in each of the three major areas; use them to construct large scale models similar to the econometric models used by a number of large consulting firms, banks, and governmental agencies.
Long Term Research: use optimizing techniques to find the best way to control multi-model for each application; develop solution techniques for differential game multi-models.

Flexible Manufacturing and Robotics

The recent appearance of new kinds of machine tools such as flexible machinery which can make a number of different kinds of items, and which can be "set up" to change from making one item to making another item in just a few seconds has provided a new dimension to manufacturing. However, the makers and users of this equipment do not know exactly how to utilize it best. It is important that research be carried out on the best ways to use flexible machinery in order to take full advantage of this new capability. In many ways a robot is a very sophisticated version of a flexible machine since it can be programmed to do a wide variety of tasks and quickly switch from one to another. The manufacturers of these new kinds of equipment and the managers of companies who own them stand to benefit from research results in the area. It is also true that industry as a whole will benefit since such results will tend to keep the United States economy competitive.

Near Term Research: discrete event dynamic systems; automatic scheduling of flexible machines; computer control of multi-jointed robots; feedback control theory; sensor technology; increase system integration.

Long Term Research: control of several robots; adaptive control of robots; use large data bases and inference machines to be able to program robots in terms of goals rather than procedures; artificial intelligence control of flexible machines (including robots).

Algorithmic and Heuristic Solutions to LSS Models

It is to be emphasized that this research should be done only in the context of specific applications in one or more of the three different subject areas. However, because of the closeness of the methods in the three areas, results obtained from an application to one area can usually be adapted to an application in another area without too much additional work. Whenever substantial improvements in solution techniques can be obtained, the solutions to design and operational problems in manufacturing and large scale systems control can be obtained more quickly and/or more accurately so that the performance in these areas can be improved. Thus, research on the practical improvement and performance of algorithmic and heuristic solution techniques for large scale systems problems to designers, manufacturers and operators of such systems in all three of the areas discussed in this report.
Near Term Research: semi-linear programming; decomposition of planning problems; constraint handling techniques; nested and hierarchical decomposition; forward programming methods; graph theoretic and heuristic solutions of combinatorial optimization problems; integer and mixed integer programming; goal programming and multiple objective optimization; finite element methods; ordinary and partial differential equations solution software.

Load Flow and Swing Equations

In order to improve our understanding of power systems it is important to carry out research to obtain a detailed understanding of the key mathematical features of the solutions to load flow (or power flow) equations. Surprisingly these systems are not fully understood even though they have been studied by many people over many years.

Better understanding of these equations will help utilities and power equipment manufacturers to improve their performance and products.

Near Term Research: Whether parallel computation of load flow equations is feasible; improve understanding of the key mathematical features of solutions to the load flow (power flow) equations such as multiplicities, stability indices, and dependence on network parameters; solution of power system models defined by swing equations with network structure by means of special reduction techniques.

1.2. Analysis of the Questionnaire

The questionnaire, which appears in Appendix A.1 was sent out to about 35 people and answers were received from 20. Of the 48 concepts on the questionnaire list all were considered significant by at least 2 people. Thirty-five out of the forty eight concepts were considered important to 10 or more of the 20 responders. The conclusion is that the group answering had a reasonably common vocabulary even though they belonged to three different engineering groups.

A listing of the concepts, together with the frequency with which they were considered to be significant by the responders appears next. Note that many of the concepts overlap or are subsets of others.

<table>
<thead>
<tr>
<th>Times Mentioned</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>computer control</td>
</tr>
<tr>
<td>19</td>
<td>parallel computation</td>
</tr>
</tbody>
</table>
computational complexity (see "NP complete", below)
decentralized control (see "multiple objectives below"
discrete event dynamic systems
decomposition
graph theory (see "network modelling", below)
maximum principle
multiple objectives
multiple variable control
network modelling
sensitivity analysis (see "reliability", below)
stochastic control theory
optimal design
reliability (see "stochastic programming," below)
stochastic programming
differential games
expert systems (see, "knowledge base", also "artificial intelligence", below)
heuristic solutions
load flow equations
super computers
knowledge base
NP complete
process simulation
artificial intelligence
branch and bound
decision support systems
robotics
flexible manufacturing
many agent players
multiple agent modelling
self organizing systems
goal programming
Stackelberg solutions

A number of additional concepts offered by the respondee are listed in Appendix A.1.

The questionnaire asked also for a list of the three most important concepts that were on the questionnaire list, or that the respondee offered on his own. These are listed in Appendix A.1.1 together with a description in the respondee's own words of what was meant by the concept. Since these are brief it does not seem worthwhile to summarize them here but to refer the reader to the Appendix for details.
Chapter 2

Concepts and Examples of Large Scale Systems

In this chapter, the idea of a system will be introduced and illustrated in terms of the three principal areas of application covered in this report; namely, Electrical Engineering, Chemical Engineering, and Manufacturing/Operations Research. Concepts introduced here will be described in more detail in later Chapters.

2.1. What is a System?

In order to avoid futile controversy, the word "system" will be treated as a primitive concept in this report. Thus, instead of attempting to give it a formal definition, a system will be described and illustrated by examples. The same remark holds for the term "large scale."

A system consists of a collection of hardware (electrical, mechanical or chemical), software (computer programs, data bases, information flows), and wetware (people). A system is created to achieve a goal or goals, which may have to be replaced with new goals from time to time. How well it does this depends on (a) how well it is designed; (b) how well it is operated; and (c) external factors (environmental, governmental, random, etc.) which cannot be controlled.

In most cases a system is operated in a repetitive manner, and its goals are stated in a time dependent way. In other words, a system is usually dynamic. For this reason it seems best to describe a system using a discrete time formulation, or analogously, as a differential equation (or in some cases, a system of partial differential equations) as follows:

\[
\frac{dx}{dt} = f(x,u,v,t), \quad x(0) = x_0
\]

where
$x$ is a vector of state variables

$x_0$ is its initial value

$u$ is a vector of control variables usually subject to side constraints

$\nu$ is a vector of exogenous variables either specified or whose distributions are specified in some way

$f$ is an influence function

$t$ is the time variable.

The influence function $f$ is determined by the hardware design and by physical laws. The control variable $u$ can be changed either by software programs or else by human decisions. Frequently, several persons or groups of persons called agents make these decisions.

In order to determine how well a system achieves its goals we introduce a system objective function

$$J = \int_0^T F(x,u,\nu,t)dt + S(x(T))$$  \hspace{1cm} (2.2)

where

- $F$ is the evaluation function

- $T$ is the horizon time

- $S$ is the salvage value function

The instantaneous evaluation function $F$ measures how close the system is to achieving its goals. The horizon time $T$ is the time interval over which the system operates; in some cases $T$ is infinity. The salvage value function $S$ measures the worth of the system if it ends at the horizon time $T$ in state $x(T)$.

The integration in (2.2) means that the $J$ value (on the left in (2.2)) represents the total value of having the system operate during the time interval $[0,T]$. Also $S(x(T))$ represents the salvage value of having the system end up in state $x(T)$ at time $T$. 
There are several complications in the description of a system which are only partially included above. We discuss those briefly as follows:

- Although not specifically noted in (1) the control variables \( u \) are limited to a specific set called the control space. These limitations are due to physical laws, legal regulations, design considerations, etc.

- Frequently the control of system lags behind the initiation of the control effort. This can be mathematically "reduced" to the above format by means of a higher order differential equation, which can in turn, be put into the form of a first order differential equation having more variables which is again of the form of equation (1).

- In many cases there is considerable uncertainty about the various quantities defined in equations (1) and (2) above. In order to include these explicitly into the notation very much more complicated equations would be required which will not be spelled out here (for instance, by means of stochastic differential equations.)

- Sometimes the information that the decision maker has concerning the state of the system is incomplete. This can be modelled by saying that he has information \( I(x) \) about the state instead of complete information \( x \), where \( I \) is a suitable function which describes the actual information transmitted to the decision maker.

The reader can doubtless think of other important factors about a system that are not included in the above description. In many cases suitable modifications can be made to include them, but in other cases considerable research may be required. For the present the above description will be adequate.

2.2. Examples

A number of examples in each of the three main areas of this report are listed next in the order of their size and complexity. At some point in each list, the system examples will reach the size where they can be said to be large scale.

(A) Electrical Systems. Some examples are:

- Power grid systems
  - In automobile
In a battleship
In the state of Hawaii
In a state in continental United States
In the whole United States
In the North American continent.

- Computer Electrical Systems
  - On a chip
  - In a computer
  - In a computer network

- Communication Networks
  - In a house
  - In a city
  - In a state
  - In a country
  - Worldwide

(B) Chemical Systems. Some of the following examples can be considered as either a pilot or full scale plant.
- Coal gasification plant
- Oil Refinery
- Complex of oil refineries
- Oil company plants and distribution system
(C) **Manufacturing.**

- Single product plant
- Job shop
- Assembly line
- Plant
- Manufacturing company together with all its subcontractors

### 2.3. Desirable Properties of Systems

As mentioned earlier, a system is created to serve a useful purpose, that is to achieve goals such as:

- To supply power to homes and factories in a given area
- To supply artificial fibers for clothing manufacturers
- To produce automobiles

It would be easy to extend these lists or to create lists for other kinds of systems. However, these will suffice for the present.

Systems can be designed well or badly to achieve their goals. Desirable attributes of system are listed next with brief descriptions of what is meant by each.

**Attractive**

Most systems are housed in buildings or other physical structures and are located in communities. In order to make them acceptable to the community, they should have an attractive appearance, cause minimal environmental impact, be nonpolluting, etc.

**Controllable**

The environment in which a system is operating tends to change over time so that the system must also change. A controllable system is one that can be easily changed over a wide range of environmental conditions.

**Economical**

Economic costs usually refer to dollars or discounted dollars but sometimes (depending on the objective) measure the negative contribution to welfare or the goal which is being maximized. There are often two important costs incurred in running a system: investment costs which are usually capitalized so that they appear as monthly fixed costs; and variable costs, which are the monthly out of
pocket costs which depend upon the output level of the system. Usually there is a trade off in the design of the system in which variable costs can be reduced by making the investment costs larger. Variable costs, such as those for energy, can change over time and this must be taken into account in the selection between fixed and variable cost levels.

**flexible**

Some systems can produce only one or a limited number of different outputs (e.g. an assembly line), while others can produce a very wide range of outputs (e.g. a job shop). It usually costs money to increase flexibility in system design, but it frequently is desirable.

**invulnerable**

As part of the design and planning process, the most violent natural and artificial occurrences, such as earthquakes, tornadoes, hurricanes, riots, etc., should be anticipated and provided for as much as possible.

**long lived**

The total cost of a system is directly dependent on its expected lifetime. The lifetime depends on the amount of capital investment, whether up to date design procedures are used, preventive maintenance procedures, etc. It also depends on how the system interacts with the rest of the economy and how it is affected by innovations, modernization of other systems, and by foreign competition.

**low pollution**

Significant investments in new systems now involve environmental studies to show the environmental impact. One of the most important factors is the amount of pollution that will be produced by the system, and the way that waste products are disposed of. Reduction of pollution usually requires capital investment.

**maintainable**

When a plant is designed so that equipment needing frequent maintenance is obstructed by other equipment needing infrequent maintenance, preventive maintenance can become very expensive. Hence maintainability should be an important factor in deciding on the location of equipment during the design of a plant.

**operable**

A system that is tightly designed, i.e., with low tolerances, tight physical space, complicated maintenance procedures, is usually difficult and costly to run. Factors affecting the operation of the system should be part of the system design.

**reliable**

Reliability is one of the most important factors in system design. It can be measured in various ways such as: amount of up time, failure probability, etc. Reliability is usually increased by increasing design factors, safety measures, etc., but these must be weighed against increased costs.

**repairable**

Repairability is another important factor which should be considered in system design. It involves predicting failures and devising procedures for repair.

**safe**

Another important factor is safety. Current laws governing labor relations require employers to provide a safe working environment. In
addition, safety procedures improve worker morale and reduce lawsuits resulting from injuries.

stable A system which is not affected greatly by random shocks and other environmental changes is said to be stable. Obviously stability improves controllability and decreases operating expenses, so should be an important design consideration.

startable The starting costs of large chemical and electrical plants can be a significant percentage of their capital costs. Hence good starting strategies, and a good design to reduce their costs are desirable.

up to date Obviously it is not a good idea to build a new plant using out of date concepts since it will, in the long run, be much more costly to operate and its life will be shorter. Hence every effort should be taken to make new designs incorporate the latest technology and even that which is anticipated to be available in the near future.

upgradable Another feature which should be included whenever possible in system design is the capability of updating and upgrading it as new developments become available. This can be done by "overbuilding" the original design.

The above is a brief listing and description of important design and management features which should be considered in planning system construction and operation. Other important factors can doubtless be added to the list. For each one can calculate the advantages of incorporating it against the cost of its incorporation. It is necessary to balance the benefits versus the costs of each desirable feature in arriving at the final design for a large system.

2.4. How Large is Large Scale?

Generally speaking when one wishes to analyze a system, one considers the effects of only a few parameters. Depending on whether one "freezes" all of the other many underlying parameters or allows them to adjust flexibly to one another usually differentiates a small scale from a large scale model.

The exact dividing line, however, which separates a "small scale" system from a "large scale" system is a fuzzy concept which must be left to the reader's discretion. Other fuzzy concepts are the attributes of being "tall", "slim", "smart", "young", "good looking", etc., when applied to a person. Everyone would probably agree that the electrical circuit in a digital watch, relatively speaking, is a small scale device, while that in a super computer is a large scale device, but where should one place the circuits in personal computers, mini computers, main frame computers, etc.? The ideas of fuzzy
Logic are described in numerous publications by Zadeh. In this report we will not use these concepts in a technical manner but keep in mind that they are not absolute concepts.
Chapter 3
Models and Algorithms

The purpose of this chapter is to present a brief survey of the most important mathematical models which have been used to study large scale systems, and to describe the algorithms which have been used to solve them. In particular, the most up to date versions of these algorithms are referred to, as far as they have appeared in the literature. The methods surveyed here are applicable, with varying degrees of success to each of the three main applications areas (electrical and chemical engineering and manufacturing) covered in this report. In later chapters we shall also discuss other models and algorithms which have (so far) been applied to only one of the three areas.

3.1. Linear Programs

One of the earliest, and without question the most successful, of the models used in modelling current industrial problems is by means of a linear programming problem, which we shall call a linear program. To state a standard linear program we need the following notation:

\[ A \] an \( m \times n \) matrix with real coefficients

\[ b \] an \( m \times 1 \) vector with real coefficients

\[ c \] a \( 1 \times n \) vector with real coefficients

\[ x \] an \( n \times 1 \) vector of primal variables

\[ y \] a \( m \times 1 \) vector of primal slack variables (used to convert primal inequalities into equalities)

\[ v \] a \( 1 \times m \) vector of dual variables

\[ u \] a \( 1 \times n \) vector of dual surplus variables (used to convert dual inequalities into equalities)

Then a primal linear program is
Maximize \( cx \)
Subject to \( Ax + y = b \)
\( x, y \geq 0 \)

The objective function is \( cx \); the constraints are \( Ax + y = b \) and \( x, y \geq 0 \). The latter are called nonnegativity constraints.

The dual linear program is

Minimize \( vb \)
Subject to \( vA - u = c \)
\( u, v \geq 0 \)

3.1.1. Primal Simplex Method

If \( b \geq 0 \) then the linear program is \textit{primal feasible}. The \textit{primal simplex method} due to Dantzig starts with a primal feasible solution and moves by pivoting (exchanging nonbasic and basic variables) toward a dual feasible solution, while maintaining primal feasibility. If \( b \geq 0 \) then the origin \( x = 0 \) is feasible. If \( b \geq 0 \) is not true then to get an initial primal feasible solution, a so-called phase-I linear program is constructed from the initial problem by adding "artificial" variables. When they have been driven out of the basic set of variables, a primal feasible solution has been found, and the primal simplex algorithm is then applied.

3.1.2. Dual Simplex Method

If \( c \geq 0 \) then the linear program is \textit{dual feasible}. The \textit{dual simplex method}, which is a special adaptation of the primal simplex method due to Lemke, can be applied. It pivots towards a primal feasible solution, while maintaining dual feasibility.

3.1.3. Pivot and Probe Algorithm

The \textit{pivot and probe algorithm} due to Sethi and Thompson adds the idea of a probe to the simplex method as originally defined by Dantzig. A \textit{probe} is a line segment in the primal space having the properties that one end of the segment is primal feasible that is, satisfies the primal constraints, while the other end of the segment is not primal feasible but has an associated dual feasible solution. We describe briefly how the method works, assuming that the origin is primal feasible.

- By "looking" in the direction of each of the coordinate axes, the first
encountered constraint is selected. The linear program consisting of these constraints (and an artificial regularization constraint which prevents the program from becoming unbounded) is solved. This gives the primal infeasible-dual feasible point which is one end of the probe; the other end is the origin, assumed to be primal feasible.

- By substituting an arbitrary point on the probe segment into the constraints not presently included in the relaxed problem the "most violated constraint", the one whose intersection point with the probe is closest to the origin is found.

- By updating and adding the most violated constraint to the relaxed problem and solving it, a new dual infeasible-primal feasible point is found, a new probe constructed, a new most violated constraint found, etc.

- The method stops when no new most violated constraint is encountered.

The pivot and probe method has improved the efficiency of Dantzig's "standard" simplex method by a factor of 5 for 300 x 300 linear programs. It does this principally by requiring a much smaller tableau to be updated at each pivot step. Efforts are underway to extend its applicability to much larger problems.

3.1.4. Semi-Linear Programming

Another extension of the simplex method to solving *semi-linear programs*, due to Fourer, also makes improvements by requiring a smaller tableau to be updated. It has the following differences from the standard simplex method.

- In the usual simplex method all nonbasic variables are set equal to zero. However in semi-linear programming the nonbasic variables, $x_j$, are instead set equal to one of a finite number of values, $s_j^k$ for some $k=1,...,K$.

- For each non basic variable set as above there are two different costs given, one giving the marginal cost of increasing the variable, the other giving the marginal cost of decreasing it.

The pivot rules for this method are considerably more complicated than for the usual simplex method, since when a nonbasic variable comes into the basis, it may go through several intervals in which its marginal costs change, and it may cause the current basic variables to go through several such intervals. However, in this way several ordinary
simplex pivots can be accomplished by making a single semi-linear pivot, so that there can be a computational saving. In addition, a single variable can play the role of several conventional variables which considerably reduces the tableau size. This method is particularly good for solving piecewise linear programs, for goal programs, and many other kinds of problems. It also is undergoing intensive development to make it more readily available.

3.1.5. Karmarkar’s Polynomial Time LP Algorithm

It has been known for about 12 years that the simplex method, although good in practice, requires exponentially many steps in the worst case. In 1979 the Russian computer scientist L. Kachiayan published an algorithm for linear programming which is polynomial in the worst case but exhibited very poor computational performance in practice.

Recently N. Karmarkar published an algorithm for linear programming that is polynomial in its worst case behavior, but also seems to provide superior computational performance. This is likely to represent an exciting breakthrough for large-scale problem solving.

3.2. Transportation and Network Models

There are special kinds of linear programming problems for which especially fast algorithms have been devised. These are transportation and more generally, network flow problems. A transportation problem is that of shipping a homogeneous good from sources to demand points in such a way that the total transportation cost is minimized. A network is a collection of nodes and arcs connecting some of the pairs of nodes. Some of the nodes are source nodes, others are sink or demand nodes, and still others are neither source nor sink nodes but transshipment nodes. The problem is to ship a homogeneous good from source nodes to sink nodes at minimum total transportation cost. Ways to efficiently solve the general multi-commodity network flow models have also been considered.

The reasons that these models are important are:

- Many large scale problems consist either entirely of network models or contain within them very large network submodels. These occur when a partially completed or completed product is shipped from one location to another.
• Very fast versions of the simplex method have been devised for solving these problems whose running times are 100 to 200 times as fast as the ordinary simplex method.

• The number of variables which can be accommodated in a network model is on the order of thousands, tens of thousands, or even millions. This makes it possible to model very complex situations without worrying about the size of the resulting problem.

Network models have been used to model and solve problems such as factory-warehouse-customer distribution problems, personnel problems, multi-stage production problems, electrical power systems, capacity expansion models, etc.

3.3. Graph Theory Models

A graph is a collection of vertices and arcs connecting some pairs of the vertices. A network, discussed above, is a graph. Many problems can be solved by special graph theoretic algorithms that do not use general linear programming methods. Examples are: shortest and longest path problems, minimal spanning tree problems, matching problems, maximum reliability problems, some scheduling problems, etc. The algorithms needed for some of these problems can be shown to run in polynomial time in the worst case and often the polynomial is of very low degree. Other problems have exponential worst case running times. The latter problems are said to be NP-complete when they can be shown to be equivalent to another problem that is already known to be in a class which includes the hamiltonian path and travelling salesman problems, minimal spanning arborescence problems, the job shop scheduling problem, etc. A good reference for this subject is Garey and Johnson.

Even though algorithms for many graph theory problems have worst case behavior that are very bad, they often exhibit excellent average case behavior and thus can be very useful. Also, it is frequently possible to devise heuristic codes which will very quickly get "good" but not necessarily "optimal" solutions to such NP-complete problems.
3.4. Mixed Integer Programs

When some of the variables in a linear program are required to take on integer values in the optimal answer the resulting problem is said to be a mixed-integer programming problem. If all the variables are required to be integer it is said to be a pure integer programming problem. Often applied problems require that some only some of the variables take on integer values. Examples are, fixed charge, scheduling, and capital investment problems. It is easy to make the requirement that such variables be integers but, unfortunately, mixed integer problems are known to be NP-complete in general. Experience has shown that they are also difficult to solve if they have very many integer variables. The latter is true not only in the worst case, but in the average case except those in which the problem also has some special structural properties which can be taken advantage of in the solution procedure. In practice, the integrality conditions are often relaxed and the continuous problem solved; then the continuous solutions rounded up or down. Another technique that works well in practice is to use branch and bound search. Much work is being done on this class of problems and more is needed.

3.5. Non Linear Programs

When the constraints or objective function (or both) of an optimizing problem are nonlinear the problem itself is said to be nonlinear. Such problems are inherently more difficult to solve than linear problems. Generally the sizes of problems that can be solved are on the order of tens or hundreds of variables and constraints as compared to thousands of variables and constraints which can easily be handled in linear programs. Most chemical processes are nonlinear and it is usually not possible to linearize them. Electrical power problems are nonlinear but frequently can be successfully approximated by means of piecewise linear functions. Manufacturing processes are sometimes linear and sometimes not, but it is usually possible to make good linear approximations to them.

3.6. Finite Element Method

The finite element method is a procedure for obtaining approximate solutions to partial differential equations having appropriate boundary conditions. It does this by discretizing the differential equations so that they are converted into matrix equations which can be solved easily on a computer. In order to discretize the problem the underlying space is divided into small chunks, called elements, and the various influence functions approximated in each chunk. The finite element method has been successfully applied to problems in chemical, civil, electrical, and mechanical engineering as well as in many other areas.
3.7. Optimal Control Theory

In a deterministic optimal control problem, a vector of state variables is considered whose values are determined by a differential equation, see Equation (2.1). The influence function \( f \) depends upon the state variable vector \( x \) and also upon the control variable vector \( u \). The problem is to find an optimal control trajectory \( u(t) \) so that the optimal state trajectory \( x(t) \) maximizes the system objective function \( J \), see Equation (2.2).

Finding answers to this problem involves the solution of a two-point boundary value problem which is, in general, a difficult nonlinear problem. Sometimes it can be solved in closed form, but more often it must be discretized and an approximate solution obtained by use of a computer program.

Optimal Control theory has been used to formulate and solve control problems in economics, production and inventory systems, personnel systems, financial systems, chemical processes, electrical processes, etc. The subject is only about 25 years old and is growing rapidly. Non linear programs and optimal control problems can be mathematically reduced to one another so that ideas developed in one field often can be usefully used in the other.

3.8. Differential Games

In contrast to an optimal control problem which has only one person or organization in charge of the control variables, in a differential game several different people or organizations are in charge of some but not all of the control variables. For instance consider two or more firms competing for a new product market. We can model this as a differential game. Another example is a power system in which there are several persons controlling various parts of the system. These persons can be at different geographical locations, can have different information about various parts of the system, can change some of the control settings on different pieces of machinery, etc. Again this problem can be modelled by means of a differential game.

Differential games are even more difficult to solve than are optimal control problems. Some approaches have been successful, but this is an area in which much more research needs to be done.
3.9. Stochastic Control Theory

Nearly all dynamic systems are subject to perturbations, disturbances or shocks which can be modelled by stochastic processes. For example, in an electrical power system demand is random, the quantity of water behind dams in a hydroelectric power system is random, the number of electrical generators in working condition and the number of transmission lines available at any one time are random parameters, etc. Similar examples can be found in the chemical and manufacturing industries.

It is also true that the information that is collected concerning the status of large systems is "imperfect", that is partial and noisy. Frequently stochastic models can be constructed to account for such noise. To solve such stochastic models we must solve problems such as identification, filtering and control. Methods for solving such problems are called stochastic analysis and control. Even simple relatively small examples of this type can lead to very large scale problems.

Therefore, there is a need for methods to cope with the complexity of stochastic control problems. Several research directions that should be followed are:

- decomposition
- multiple time scales
- perturbations (singular or regular)
- linking of less detailed long-term models with more detailed short-term models
- Monte Carlo simulation combined with classical optimization methods

It is likely that the use of computer assisted tools will be very useful in carrying out the research needed.

3.10. Simulation

Instead of formulating a system model as a linear, nonlinear, optimal control, or differential game model, some researchers prefer to describe its operation in detail in a step by step manner depending on a time parameter. Several simulation languages exist which make it easy to do this. Once the model is specified by a series of simulation statements it can be run on a computer and its behavior observed in the simulation run. In this case there is no formal attempt to optimize the resulting model but merely to keep
changing its description until the observed behavior of the simulation model is sufficiently close to the real system that it is considered to be a satisfactory model. Then small changes can be made and the simulation rerun to see whether improved performance is observed.

Simulation models are used for problems that are so complicated that optimizing models are difficult to formulate or else difficult to solve once formulated. They often produce usable feasible, even though not optimal, solutions. In solving dynamic linear programs by the dual nested decomposition approach, the proposal has recently been made to approximate the solution of the stochastic subproblems by means of simulation.
Chapter 4
Recent Accomplishments in the Three Systems Areas

A brief discussion will be given of the recent accomplishments in each of the three systems areas covered by this report, Electrical Engineering, Chemical Engineering, and Manufacturing/Operations Research. The content of this chapter is taken largely from the presentations of the panel members at the Workshop on Large Scale Systems held in Pittsburgh on March 26-27, 1984.

4.1. Electrical Engineering

1. Design

   a. Electrical power systems, as opposed to computer systems, are for the most part stationary and already in place. There is little opportunity to improve on the current design of that system.

   b. For the same reason, only tiny incremental changes can be made in the system: a few plants can be closed, a few opened and those that are opened must conform to the existing system rather than be designed from scratch.

   c. For these reasons the current power system can change only slowly and incrementally. It is not possible to change previous decisions such as, for instance, the 60 cycle frequency and 120 volts which are the US standard.

   d. Power plants, substations and the electrical wires which carry power have lifetimes measured in decades. Whether or not they were designed correctly for the conditions when they were installed, it is almost certain that towards the end of their useful lives they are more or less inadequate for the purpose.
e. Electrical power is one of the few commodities which is, by laws of physics, absolutely homogeneous and of uniform quality, the only variations being the minimum voltage level, which is usually determined by regulatory agencies. It is also not directly storable, although it can be converted to other forms of energy which can be stored. Hence the "peak load" problem is of great importance to the industry.

f. In the United States (but not in many other countries) electrical power is controlled by multi-level decentralized organizations. Power companies are usually, but not always, contained within a state; consortia of companies are divided into regions; etc. Coordination among these organizations is more or less loosely controlled by governmental agencies who have limited powers to enforce their wishes.

- When a power company designs a new plant, or redesigns an old plant its major consideration is its own "bottom line", and the effect of the new plant on the power grid into which its power is fed is not one of the principle factors which is taken into consideration.

- In the same way, when a plant is controlled by a given company, the safety of its own equipment is often a more important consideration than that of the larger system in which it operates.

g. Accurate forecasting of demand in either the near term or far term is important in the design, redesign, and control of a power system. The system must also be prepared to meet the effects of prolonged hot or cold spells, not enough water in the reservoirs due to lack of rainfall, temporary unavailability of various kinds of fossil fuels, etc.

- Daily demand for a given region follows a fairly predictable pattern. Usually there are two or more peak demand intervals with reduced demand in between. In order to meet this demand efficiently the system must have available a variety of different generators--some with large output and low cost, and others with smaller output and higher costs to meet the peak demands.

- To estimate the long term changes in power demands in a given region it is necessary to predict how the current pattern of
growth will proceed in that region. This involves statistical, economic and demographic factors.

h. Long term growth of the economy requires the design, siting and construction of new power generation and distribution facilities. Different parts of the new system require various amounts of time to construct.

- In order to construct a new transmission line it typically requires a period of approximately 3 years to design it, acquire rights of way, and build it.

- A new energy generation plant requires around 8 years to design, obtain approval, and construct. Nuclear power plants can take even longer.

- Storage units can be very useful in "smoothing" the daily load cycle of a power generation unit. However, these units are usually physically large, frequently disturb the environment, and are costly. They can take 8 or more years to plan and construct.

2. Modelling

a. Current state estimation is static and is made by solving overdetermined load flow equations. A dynamic state estimation method is needed.

b. Voltage profile estimation techniques have been recently developed. Needed is the solution of the voltage profile problem, which is a nonlinear control problem connected to the megawatt control problem.

c. When a large system is controlled by several different agents, each one of which may be an individual or an organization, it is likely that each agent will perceive the system from a different point of view. An example is the sale of electrical power by one utility to another. In other words each agent will have his own version of a model of the system. In order to model how the system will be controlled by these agents a it is necessary to create a model for each and then put them together in a "multi-model" of the system.

- The resulting model will have decentralized descriptions of:
the way information is sent and received by the various agents;

- the models which the various agents have of their own part of the system and that of other agents;

- the way that the individual control variables affect the system.

- The various agents will have individual objectives primarily for their part of the system and only secondarily for the rest of the system. These objectives may include: reliability; safety; flexibility; robustness; esthetics.

- The subsystems will interact in areas where their spans of control intersect. Large systems will tend to be leaders and small systems followers. It is necessary to model this kind of behavior.

- Different agents will act according to different time scales. For instance:
  - Control of transients requires timings on the order of tenths of seconds.
  - Economic dispatch controllers must react in seconds to load changes.
  - Long term dynamic changes in system parameters must be adjusted in times measured in minutes or hours.
  - Unit commitment schedules are made with days as time unit.

- Stochastic elements are important in several part of the control problem such as:
  - In estimating machine parameters.
  - In estimating loads and power capabilities.
- In estimating the reactions of neighboring power systems.

- In estimating hydroelectric reserves.

3. Models and Related Solution Techniques. We list below a number of important problems in the Electrical Engineering area together with a corresponding solution technique.

a. A power network having convex costs can be modelled by means of a piecewise linear network model. Because of the extreme speed of solving network linear programs, very large models can be solved quickly.

b. Currently attempts are being made to solve load flow equations by using computers that are capable of parallel processing.

c. Power system models, defined by swing equations incorporating a network structure, are currently being solved by using special reduction techniques which identify coherent generator groupings based on eigenvalue analysis and singular perturbation/weak coupling methods.

d. The stochastic gradient method has been used to solve a transmission system planning model. It was shown to be superior to a linear programming approximation that was solved by standard linear programming software.

e. Advanced computational methods have been developed for solving the operations (unit commitment) scheduling problem.

f. A quadratic variational inequality model has been formulated for the stochastic unit commitment scheduling problem.

g. Singular perturbation and team theory involving local feedback control have been used to develop reduction techniques for a stochastic control model of a large scale (> 200 states) hydro-power production system. Optimal control and differential games models can be solved numerically by using finite difference and finite element approximations.

h. Because of the limited availability of super computers up to the present
date, it is difficult to predict how much they will add to the solution capabilities of current techniques. Since super computers are likely to become more available in the near future, it is easy to predict that they will make considerable difference in the sizes of problems that can be solved.

4. Management. The problems faced by the management of power industry are twofold: first, meeting current demand under normal conditions and making provisions to handle the system under abnormal conditions; and second, planning how to meet future demands. We discuss these problems briefly.

a. Normal conditions.

- A power system must be demand responsive, that it must meet realized demands with very high probability since absolute certainty of demand fulfillment would be too costly.

- It is possible to view a power system as being composed of four subsystems:
  - A fuel management subsystem;
  - An electric power generation subsystem;
  - A power transmission subsystem.
  - A power distribution subsystem.

- Different time scales are needed for system operation:
  - To control transients, reaction time must be measured in tenths of seconds.
  - To solve the economic dispatch problem, the reaction time can be measured in seconds.
  - To control long term dynamic changes, the reaction time can be measured in minutes.
  - To solve the unit commitment problem, the reaction time can be measured in days.
• Fuel contracts which utilities sign must not contain terms and conditions which could turn out to be economically or otherwise unattractive and which may lead to adverse publicity by citizens groups. Governmental regulations must also be taken into account.

b. Abnormal conditions. Active control is needed:
• To remove line overloads, high and low voltage conditions, and to take into account insufficient reserves.
• To balance power generation and load.
• To damp frequency and power oscillations.
• To restore service after failures.

c. Long term management of power systems must do the following:
• Forecast future demands for power including the geographical locations, amounts, and types (residential or commercial) of future demands.
• Determine the types, sizes, and timings of new energy generation and storage units.
• Determine the types, sizes, locations and timings of new transmission and distributions lines and substations.
• Determine cost and quantity of various future power sources and fuels and potential contracts and conditions.

4.2. Chemical Engineering

1. Design problems are especially important in chemical engineering because chemical plants are very expensive to build, have long life times, and produce large quantities of output. Many plants in the US are old and were designed when energy was cheap. Some need to be redesigned, and others will probably be closed down and their replacements build abroad. Important factors in design are:
• Synthesis, which is the process of inventing a new structure to perform a required task.

• Analysis, which is the process of discovering how the proposed structure will work in practice.

• Control, which is the process of discovering how the structure can be run most efficiently to perform its task.

2. Modelling of chemical and petroleum processes industries.

• In order to describe the full scale of chemical engineering problems it is necessary to describe the hierarchy of large scale systems in chemical and petroleum processes industries. The various levels of organizational structure are listed next.

  ■ Multinational companies have plants and plant complexes in a number of different countries. The problem is to coordinate production, distribution, income, among the various plant locations to minimize tax consequences and enhance profits. Such companies obey the laws of each country in which they exist as if they were foreign owned.

  ■ National companies have their primary production and distribution facilities all in one country. Their product is sold in that country, and in some cases exported to other countries. These companies must obey the laws of that country.

  ■ In some cases companies own a plant complex which consists of several plants located on the same site.

• Modelling techniques include the following:

  ■ The flow sheeting technique is a computer program in which a physical process is represented in the computer in such a way that once settings of various parameters are given the output of the program is the output of the physical process. It would be possible to put the physical properties of a given chemical system on a chip so that the response of the flow sheet program would be very fast. A good flow sheeting program should have a
library of alternative equipment possibilities and their physical properties so that many different designs of a given process and settings of equipment control and design parameters can be created and evaluated quickly.

- In order to indicate the magnitude of the flowsheeting programs for various large scale systems of chemical and petroleum processes, the typical sizes of the flowsheeting problems for some of the systems given previously are listed next:
  
  - For an individual plant having many separate units there can easily be one million different possible flowsheets; the number of nonlinear (algebraic) equations per flowsheet, about one thousand; the number of different optimizations needed per flowsheet, about ten. Multiplying gives 100 billion different optimizations that must (potentially) be performed in order to do a complete flow sheet analysis.

  - For an individual process unit from ten thousand to one million different modes of operation must be considered.

  - It is clear that research should be directed to reducing the number of different cases that must be considered.

3. Solution techniques for solving process synthesis problems include the following:

- Large scale problem solving techniques such as:
  
  - For multinationals, nationals, and plant complexes: structured linear programming and linear input-output models.

  - For plants: flow sheets and nonlinear optimization: mixed integer nonlinear programming, ordinary differential equations and partial differential equations, heuristics.

  - For individual units: flowsheets, finite elements, finite differences, collocation.

- Software needed in following areas:
- Ordinary differential and partial differential equations packages;

- Flow sheeting;

- Sparse matrix techniques;

- Large nonlinear programming methods;

- Solution of optimal control problems.

- Hardware advances needed in following areas:
  - Vector manipulations and parallel computation;
  - Super computers;
  - Chemistry on a chip, that is, constructing a chip which contains all of the equations needed to define a given process.

- Other techniques that are frequently used are:
  - Heuristic programs to weed out bad ideas and to create "good" ones cheaply;
  - Artificial intelligence to help engineers to better organize and draw on their collective experience.

- Simulation is routinely used:
  - At the screening stage to get crude but fast answers;
  - At the design stage to get accurate answers with more sophisticated hence slower programs.

4. Management problems connected with operating a plant include:

- Scheduling problems are commonly found in the chemical engineering industries. Examples are:
  - Plant operations such as scheduling of different products through the plant;
Corporate operations such as scheduling planned expansions or shutdowns, scheduling of production allocations to different countries.

- The control of chemical plants is similar to the control of other manufacturing plants whether continuous process or batch. For instance the control of a batch chemical process is almost identical to the job shop scheduling problem in manufacturing.

4.3. Manufacturing/Operations Research

1. Design

- The manufacturing area differs from the previous areas in that it covers the production of thousands of different products, which themselves may contain thousands of different parts. Some factories produce products which they themselves market, while other factories produce intermediate products which are themselves used as inputs by other factories. At the base of this pyramid of manufacturing are the raw materials industries which produce the essential primary goods.

- There are many kinds of manufacturing methods used by the manufacturing industries such as:

  - Job shop manufacturing in which a large number of different items are made in very small batches (typically one or two) in a random order so that a substantial setup and re-learning period is needed at the beginning of production of each batch;

  - Flexible manufacturing is a relatively new method which is made possible by having a large machine which is numerically controlled and which has a battery of tools that can be quickly changed so that the machine can be setup almost instantaneously for the production of any one of a number of items; there are also available a number of transfer machines which bring partially finished pieces to the flexible machine for the next step in their manufacture;

  - Repetitive manufacturing in which a factory produces a number of different products in sufficiently small batches that it does not pay to set up an assembly line;
Assembly line manufacturing in which the same product is to be manufactured for a very long period of time—automobiles are the principal example.

Another factor in current economies is the rapid introduction of new products. The average life of a product from the time it is first marketed until it is superseded, is about 10 years, which is hardly long enough for the factory to learn how to produce it efficiently.

New manufacturing methods are constantly being introduced such as numerically controlled machine tools, robots, workers, flexible manufacturing, powdered metal forming, composite materials, continuous casting, etc.

There is a strong tendency for current businesses to become international and for markets for products to become global. For this reason it is necessary to use every method to keep costs down and to use current technologies in order to keep a business competitive in the world market.

Production decisions have strong interactions with finance and marketing decisions. In the past, decisions made in these three departments have been kept separate, but it has become obvious, to keep competitive, that there must be coordination between the decisions made in each.

The construction of a new factory which is to be part of larger production distribution system requires the solution of several problems such as:

- Where should the factory be located? Ideally it should be located close to a demand center, close to good transportation facilities, and also close to one or more finished goods warehouses, warehouses and low capital costs. In practice not all of these ideals can be achieved and a compromise must be reached. Good siting can make a large difference in the operating costs of the factory.

- How should the machines be located in the factory? Once the location of the factory has been determined it is necessary to
decide how the various machines in the plant should be located in order to have a smooth flow of partly finished material through the plant and to minimize the in plant transportation costs.

- Which warehouses should be assigned to receive the factory's output and which final customers should they service? The problem is to determine how much of the factory's output should be assigned directly to local customers and how much should be sent to the various company's warehouses for eventual reshipment to customers.

- There are a number of warehouse problems which are similar to those described for factories, such as:
  - Where should the warehouse be located? Ideally it should be located near one or more large demand centers, near to transportation facilities, and within reasonable distance of the company's factories. In practice, it may not be possible to achieve all of these simultaneously and a compromise must be found.
  - What should be the size of the warehouse? Factors to be considered in this decision are: the cost of later enlarging the warehouse, the cost of renting other storage facilities, the expected future growth of the market, etc.
  - Which warehouses should be assigned to service a customer? Usually only one warehouse is selected to service that customer (the 'single sourcing' requirement). However, in the event of an exceptionally large order by a single customer it may be necessary to assign more than one warehouse to him.

2. Modelling the operations of a plant.
  - The most usual way of operating a plant is to set up a hierarchical control system. The top plant management sets goals for each of the divisions, the division managers set goals for the foreman, etc. Specific decisions about the operation of an individual machine are made by the machine operator. Because the individual decision maker usually does
not have the company's objectives in mind at all times, or, as is more likely, does not have the capability of weighing the effects on the company of alternative actions on his part, this control scheme results in suboptimal performance. Research is needed to improve on this control technique.

- Every plant that has more than one machine or more than one product or more than one worker encounters scheduling problems. Products such as cars involve thousands of parts, and since each kind of car has several different models the problem become even larger. A number of different procedures have evolved for solving these scheduling problems.

  - The most common way of solving scheduling problems is to use heuristics or "rules of thumb" in making the decision as to which item a given machine should work on next. Two common rules are: "work on the item which can be completed most quickly"; or, "work on the item that has the largest remaining processing time." Heuristic rules often produce reasonably good decisions but are rarely optimal relative to the firm's overall objective.

  - Japanese firms have developed the "just-in-time" philosophy which says that a part or subassembly should not be produced until the last possible moment before it is needed, except for the relatively few products that are being processed on the "bottleneck" machines. Following this philosophy reduces the work-in-progress inventories. The method is implemented by the Kanban or work order ticket system.

  - The hierarchical scheduling system proceeds in two stages: first the stream of orders for finished goods produced by a plant is broken down into weekly demands for the various parts and subassemblies that go into it; then detailed production plans for each of the machines that produce the parts and subassemblies are constructed to meet the weekly demand goals.

  - A relatively new development in manufacturing is the appearance of "flexible" numerically controlled machines which have stored programs for making a wide variety of different goods and a bank of tools which can be changed quickly so that the setup time
required to go from making one kind of good to making another is very small. An important problem that is currently just being addressed is that of deciding which of a number of different goods waiting in front of a flexible machine should be chosen to be processed next.

- Robots are now being used to perform dirty, dangerous, or repetitive steps in manufacturing, and the number of them being used is growing very rapidly. With the development of new sensory capabilities such as vision, they can be used for the more delicate manufacturing steps. A number of important problems require solutions for this to happen.
  - Software tools are needed to generate a mathematical description of the statics, kinematics and dynamics of a robot. Further software tools are needed to design the electromechanical systems that make the robot perform the desired task.
  - Feedback control theory is needed to design controls that detect the buildup of oscillations and vibrations and decouple the system at the kinematic level.
  - A number of computer science developments are needed including the design of special purpose computer controllers, the design of special purpose languages, and the analysis of algorithms.
  - Needed sensor technology developments include vision sensing and vision algorithms, force sensing, and tactile sensing.

- An important problem faced by large manufacturing plants is the assembly line balancing problem which requires the determination of the location of work stations and the allocation of the work to be done by each station so that all work is performed in proper technological order, with enough time given the speed of the line for each worker to do his job, and that the optimal number of workers is assigned to the line.

- Modern production methods have inventories at several different levels including work in progress, finished goods, and spare parts inventories. Their management is a major problem which has impact on sales and
profits as well as on the production system. The classical solution
technique of calculating the economic order quantity lot size is being
modified to take into account some of these higher level effects.

3. Solution Techniques for the Models. Having discussed the nature of the
planning problems in the area of manufacturing, we now classify them and
list the solution methods that have been used to attack them.

- Long term planning: multi-stage (staircase) linear programming
- Short term planning: mixed integer programming
- Scheduling: integer programming; heuristics; simulation
- Location: mixed integer programming; heuristics
- Assembly line balancing: heuristics; simulation
- Job shop scheduling: mixed integer and parametric linear programming;
  heuristics; simulation.
- Layout: quadratic assignment; heuristics.
- Flexible manufacturing: discrete event dynamic systems.
- One machine scheduling with dependent setup times (which is a
  travelling salesman problem): graph theory; mixed integer programming;
  heuristics.

4. Management of Manufacturing Enterprises

- Normal Conditions
  - Partly due to Japanese competition, it has been recognized that
    one way to reduce costs is to keep work-in-progress inventories
    low, especially in front of machines which are not bottleneck
    machines, i.e., which have less work to do than the bottleneck
    machines. Companies are seeing that this factor is better than
    accounting rules based on such concepts such as high efficiency
    or high utilization of a given machine.
A corollary to this is the rule: keep bottleneck machines busy.

Another lesson learned from the Japanese is that "quality comes free," in the sense that reworking or repairing bad products is much more costly in both out of pocket costs and loss of good will than producing essentially perfect products.

**Abnormal Conditions**

- Reduction of down time, due either to breakdowns or maintenance is important especially for bottleneck machines. Built in flexibility in production sequences is valuable in being able to cope with down time problems.

- When a bottleneck machine is delayed, its lost output causes delays in the machines which occur later in the production process due to lack of items to work on. It also causes build up of partly finished goods before the bottleneck machine. Both these problems can be solved, at least partially, by having buffer inventories before and after bottleneck machines (which are relatively few in number).

- In many cases expediting may be the only way to get critical production out. If it is necessary to almost always resort to expediting, however, it can markedly reduce the overall efficiency of the plant.
Appendix A  
Questionnaire on  
Large Scale Systems Research Concepts

A.1. The Questionnaire Results

The questionnaire was sent out to approximately 35 people and answers were received from 20. The directions for the questionnaire followed by a summary of the answers follows.

*Directions.* Please take a few moments to *quickly* answer this questionnaire by stating for each concept listed whether it is presently, or is likely to become important in your research in large scale systems. If you haven't heard of the concept, answer "Don't know." Then list any concepts which are not included on the last page of the questionnaire. At the end list the three most important concepts of all those mentioned.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Relevant to my area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>1. NP complete problems</td>
<td>13</td>
</tr>
<tr>
<td>2. computational complexity</td>
<td>18</td>
</tr>
<tr>
<td>3. load flow equations</td>
<td>14</td>
</tr>
<tr>
<td>4. expert systems</td>
<td>15</td>
</tr>
<tr>
<td>5. process simulation</td>
<td>13</td>
</tr>
<tr>
<td>6. bio-processing fermentation</td>
<td>2</td>
</tr>
<tr>
<td>7. process synthesis</td>
<td>5</td>
</tr>
<tr>
<td>8. flexible manufacturing</td>
<td>11</td>
</tr>
<tr>
<td>9. discrete event dynamic system</td>
<td>18</td>
</tr>
<tr>
<td>10. maximum principle</td>
<td>17</td>
</tr>
<tr>
<td>11. multiple variable control</td>
<td>17</td>
</tr>
<tr>
<td>Title</td>
<td>Pages</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>12. operations scheduling--unit commitment</td>
<td>15 3  2</td>
</tr>
<tr>
<td>13. stochastic control theory</td>
<td>17 2  1</td>
</tr>
<tr>
<td>14. decentralized control</td>
<td>18 2  1</td>
</tr>
<tr>
<td>15. differential games</td>
<td>12 5  3</td>
</tr>
<tr>
<td>16. multiple agent modelling</td>
<td>11 2  4</td>
</tr>
<tr>
<td>17. Stackelberg solutions</td>
<td>10 4  4</td>
</tr>
<tr>
<td>18. many agent players</td>
<td>11 3  4</td>
</tr>
<tr>
<td>19. artificial intelligence</td>
<td>12 3  3</td>
</tr>
<tr>
<td>20. knowledge base</td>
<td>13 3  3</td>
</tr>
<tr>
<td>21. goal programming</td>
<td>10 2  7</td>
</tr>
<tr>
<td>22. forecast horizons</td>
<td>8   4  7</td>
</tr>
<tr>
<td>23. forward methods</td>
<td>8   3  8</td>
</tr>
<tr>
<td>24. branch and bound</td>
<td>12 3  2</td>
</tr>
<tr>
<td>25. heuristic solutions</td>
<td>14 4</td>
</tr>
<tr>
<td>26. means ends analysis</td>
<td>5   4  11</td>
</tr>
<tr>
<td>27. decomposition</td>
<td>17 2</td>
</tr>
<tr>
<td>28. sensitivity analysis</td>
<td>17 3</td>
</tr>
<tr>
<td>29. robotics</td>
<td>12 7</td>
</tr>
<tr>
<td>30. computer control</td>
<td>19 1</td>
</tr>
<tr>
<td>31. self organizing systems</td>
<td>11 3  4</td>
</tr>
<tr>
<td>32. optimal design</td>
<td>16 1  2</td>
</tr>
<tr>
<td>33. stochastic programming</td>
<td>16 3</td>
</tr>
<tr>
<td>34. semi-linear programming</td>
<td>8   5  4</td>
</tr>
<tr>
<td>35. network modelling</td>
<td>17 4</td>
</tr>
<tr>
<td>36. goal-on-arc networks</td>
<td>3   4  11</td>
</tr>
<tr>
<td>37. generalized assignment problem</td>
<td>9   5  3</td>
</tr>
<tr>
<td>38. generalized transportation problem</td>
<td>8   7  4</td>
</tr>
<tr>
<td>39. graph theory</td>
<td>17 4</td>
</tr>
</tbody>
</table>
Evidently nearly all of the concepts listed were found to be of importance to most of the respondents. At the same time, nearly every respondee also listed some additional concepts which he believed to be of importance. These are listed next.

**Additional important concepts**

- adaptive and robust control
- adaptive multiagent modelling
- advanced numerical techniques
- aggregation
- approximation methods based on local optimization
- asymptotic analysis
- bioprocessing separations systems
- bioprocessing systems design
- combinatorial optimization
- communication costs
- computer aided design
- computer aided engineering
- computer networks
- continuation techniques
- control of unstable systems
- cutting planes
- decentralized decision theory
- decentralized estimation theory
- decoupled control
- digital communications
- disjunctive programming
- distributed asynchronous computations
- distributed computer control systems (and decentralized control)
- distributed control and estimation
- distributed detection
- distributed detection and estimation
- distributed estimation
- distributed optimization
- dynamic model simplification of large scale systems
- dynamic programming
efficient screening of a large number of alternatives
empirical testing of algorithms and heuristics
estimation and modelling of multiagent systems
feedback principles for multiagent control
hierarchical systems theory
human operator theory
incentive strategies for hierarchical control
information integration
information management
integer and mixed integer programming
limitations on the applicability of direct methods
for power system stability analysis
man-machine systems
mixed integer nonlinear programming
mixed integer nonlinear variational optimization
more complete understanding of the mathematics of the
load flow equations
multi-terminal communications
multi-terminal information theory
multi-time scales in system modelling
multiple time scale phenomena (slow-fast motion)
on line dispatch and control
on line stabilization
operation and control in aerospaces
optimal control
optimization based computer-aided-design
pde-continuum models
physically based models of the dynamics of
interconnected electrical machines
priorities of controls
quadratic programming
random access communications
reactive power management
relational data management systems
relaxation methods (subgradient optimization)
self-tuning for large scale systems
sensitivity studies, parameters and nonlinear
model structure
sensors
singular perturbation methods
singular perturbations
software development and tools
sparse matrix techniques
stability and convergence
state estimation
team theory
textured systems
user-friendly portable software packages
vision systems
VLSI realization of problem specific algorithms
A.1.1. List of "Three Most Important Concepts"

At the end of the questionnaire, each person was asked the following question: "Of all of the above concepts please choose the three most important to your area and list them below together with a sentence or two explaining why they are important." The response to this question was very informative. The answers are listed (almost) verbatim below.

G. L. Blankenship

1. Stochastic Control. General methodology for modeling and design of large classes of systems.


3. Expert Systems. Not used much in control theory but will become important to apply artificial intelligence ideas for design of control systems.

Roger Brockett

1. Computer Control. Computers are now very capable of doing a better job of controlling complex nonlinear systems but we lack the means to realize their full potential.

2. Robotics. Robotics is a test bed for many control problems which involve large and weakly structured systems. The methods which are useful in robotics will be copied in other areas.

Jose B. Cruz, Jr.

1. Incentive Strategies for Hierarchical Control. In multiagent multiobjective problems, it permits coordination by the leader in such a way that the followers' objectives become aligned with the leader's.

2. Feedback Principles for Multiagent Control. The uses of feedback in single controller problems are well-known. Its potential for robust strategy design in large scale systems with multiple decision models should be investigated.
3. **Adaptive Multiagent Modeling.** In multiagent models, it is critical that each agent extracts as much information (on-line) to discern the strategies (and models) being used by others, and to adapt its model and strategies accordingly.

   George B. Dantzig

1. **Decomposition.** Optimizing small chunks of a problem and combining the results using some kind of recursive approach.

2. **Stochastic Aspects.** Designing systems and their adaptive control so that the systems are resilient in face of uncertainty.

3. **Hierarchy of Interacting Models.** Long term models sets goals for the short term detailed models to follow.

   James M. Douglas

1. **Process Synthesis.** To develop the *knowledge base* and *heuristic solutions* that can be used in *expert systems* to develop *optimal designs*. Reasons: Many people believe that the production of commodity chemicals in the U. S. will not be competitive in the near future and will move overseas. Thus procedures for retrofitting existing plants to make them more competitive is an important problem. We need better computer tools in an "engineering work station."

2. **Optimal Control.** Including multiple variable, decentralized computer control. Reasons: Again, we need improved control to make our existing plants as profitable as possible to make the funds available to move into new areas.

3. **Bioprocessing System Design.** Biotechnology will provide a radically new approach for making chemicals and new products. Most current research is focussed on "genetic engineering" and fermentation, but preliminary "systems evaluations" indicate that the major costs will be in separations problems, so that new separations technology is needed.
1. **Relational Data Management Systems.** One solution to certain classes of computational complexity is to manage the data independently from the programs that use the data. This is certainly helpful in computer aided design and in process synthesis.

2. **Knowledge Base.** Methods for acquiring, encoding, or generalizing knowledge are needed to support expert systems, e.g., process synthesis, and optimal design procedures.

3. **Multiple Objectives.** It is no longer adequate to optimize designs on the sole criterion of costs or profits. Other measures of design quality must be considered, such as resiliency, reliability, environmental safety, etc. Techniques for optimizing under multiple criteria are needed.

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**Maurice Robin**

1. **Stochastic Control.** This area covers a very large spectrum of problems and models in numerous fields, and we can expect efficiency improvement from it.

2. **Methods to Reduce Complexity of Models.** Examples are decomposition, multiple time scales, etc. One needs such methods to obtain tractable problems from large scale models.

3. **Computer Aided Engineering Including Artificial Intelligence Tools.** It is one way to cope with complexity and, at the same time, to incorporate more interaction between applications engineers (of the field concerned) and the control engineers.

---

**Arthur W. Westerberg**

1. **Process Synthesis.** Process synthesis provides tools to aid engineers to design better processes. It also offers a methodology that can be taught. The impact on design is often significant.

2. **Decomposition.** This is not single concept but the whole idea is to allow much larger problems to be solved. Many elegant theories flounder on implementation details, of which decompositions are an essential part.
3. **Finite Element.** Offers a method to permit complex distributed models to be analyzed.

Michael Athans

1. **Distributed Optimization.** Large scale systems cannot operate under centralizing rules. Thus, we must develop fundamental understanding of how distributed decision agents carry out implicit and explicit optimization with limited communications.

John Baillieul

1. **Load Flow Equations.** The load flow equations are one of the most widely used analytical tools in both long and short term planning for electric utilities. Nevertheless, very little is currently understood (even for small networks) about such important questions as how changes in network parameters influence solutions.

2. **Models of Interconnected Machines.** The classical "swing equations" models used in stability analysis are not valid during power system transients.

3. **Limitations on Direct Methods.** Both the utilities and government have spent considerable amounts of money studying such methods. Because our current limited understanding of both dynamic and steady state power system models, however, it is not clear what are appropriate applications of these methods.

Egon Balas

1. **Approximation Methods Based on Local Optimization.** Such methods are superior to heuristics based on emulating human behavior, since they provide means of using partial knowledge of problem structure more complex than humans can handle.

2. **Empirical Testing of Algorithms and Heuristics.** Too little of it is done, while no efficient method has ever emerged without it.

3. **User-friendly Portable Software Packages.** They make our techniques into a mass product.
John S. Baras

1. **Distributed Asynchronous Computations.** Because all functions in a large scale system have to be performed in such a fashion.

2. **Multiple Agent Modelling.** Because existing models do not permit satisfactory treatment of information patterns.

3. **Expert Systems.** Because the future control systems for large scale systems must include a layered structure (due to complexity). The higher level of this structure will incorporate expert systems.

Toby Berger

1. I see systems theory as dividing into 4 subdisciplines:
   - Communication/Information
   - Decision
   - Estimation
   - Control

2. For large scale systems it is necessary to develop decentralized versions on these fundamental areas of inquiry. You cite on your list only decentralized control (14), although (9), (15), (16), (17), (18), and (19) are in the spirit of the other three. Perhaps these more general designations would be helpful for organizing the discussion.

C. Y. Chong

1. **Information Integration/Management.** A power system is flooded with large amounts of data. Aggregation of this data in a form suitable for the operator, especially in emergencies, is critical.

2. **Man-Machine Systems.** Performance of a system can only be optimized if humans can work with machines.

3. **Distributed Estimation.** Many operators are present and all have some estimates of the state of the system. Their estimates should be consistent.
Charles Herget

1. *Decomposition.* Essential to the ability to analyze and design controllers for large scale systems.

2. *Multi-variable Control.* The heart of the problem we're interested in.


Robert E. Larson

1. *Dynamic Programming.* Dynamic programming is extremely important to me as a powerful approach to formulating optimal control problems in electric power, chemical processes, and manufacturing. It always provides a useful framework for developing approaches to solving these problems, and it is often useful as an algorithm for implementation in the solution as well.

2. *Software Development Methods/Tools.* Software is becoming the dominant cost in computer systems, particularly for real-time semi-custom systems. Improved productivity and cost reduction here is badly needed to allow improvements in hardware to attain full value.

3. *Supercomputers/Computer Networks/Parallel Computation.* Improvements in computer architecture and basic computer circuits are increasing speeds and reducing costs at an astronomical rate. Continued progress will revolutionize the control field, assuming the difficulties with software in #2 are resolved and good problems are formulated as in #1.

Yu-Chi Ho

1. *Discrete Event Dynamic Systems.* These are NP complete problems arising in flexible manufacturing situations. One solution approach is by perturbation analysis.

2. *Information and Games.* See concepts 13-17.

3. *Information Processing Systems.* See concepts 44-48. Remarks on #2,3. The explosive growth of computer hardware has outdistanced the corresponding advances in "software." I use software in the general sense to include all
tools for the management of hardware. In other words, the "system" problems associated with information processing equipments. Business Week predicted that by 1990 we'll be giving away computer hardware. In particular I see two major thrusts:

- **Utilization of Information.** The purpose of information is to make better decisions. In an increasingly tight coupled world such as ours, we are generally facing decision problems which involve more than one such decision maker, each having access to different information. In such game-theoretical and economic settings, the issue of "who knows what when" becomes important. Current hot topics among mathematical economists, such as perfect and sequential equilibrium concepts, incentive compatibility, all address issues arising out of this context.

- **Efficient Management of Information Systems.** Growth of the disciplines such as flow control of communication networks, performance evaluation of computer systems, are all symptoms that we have a long way to go in learning to solve computer "system" problems. A lot has been done but much more remains.

Hassan Khalil

1. **Decomposition.** A key point in the analysis and design of large scale dynamic systems (e.g., power networks) is the decomposition of the system into small interacting units which can be analyzed at different hierarchical levels.

2. **Multiple Time Scale Phenomena.** Multiple time scale phenomena arise naturally in almost all large scale dynamic systems. Developing systematic procedures for recognizing such phenomena and exploiting it for temporal decomposition of the system is an essential element.

3. **Decentralized Control.** With the increasing use of microprocessors and microcomputers, there is a definite need for developing a theory for designing distributed control. Decentralized control is one step in that direction.
Umit Ozguner

1. *Interrelation between Information Structure and Computational complexity.* It is becoming evident that "optimal" control is achievable under decentralized information if more complex algorithms are used in real time. A major effort is required to assess the relation between satisfactory or optimal behavior of a controlled large scale system and the "cost" required to implement the information channels, and also the "cost" required for the calculation of the controls.

2. *Multimodelling.* Different control agents have different models of a decentralized system, which may even change according to the control influence exerted by others.

Gerald L. Thompson

1. *Algorithm Improvements.* Continued efforts are needed to improve existing linear and nonlinear solution algorithms. Current methods include: forward algorithms, horizon detection, and natural decomposition: use of probes to identify essential constraints: and problem-expanding techniques.

2. *Facilitate User-Algorithm Interaction.* The end user (manager) of a model of a large scale system should be able to easily change parameters in the system via a decision support system. By means of a knowledge base and an expert system the user should be able to get and give advice on the progress of solving a model of the system.

3. *Optimal Control and Differential Game Models.* Most systems have to be controlled over time by one or more agents: these can be represented naturally by optimal control and differential game models. Such models are also useful in studying monopoly and oligopoly economic situation which occur, for instance, in new product introductions.

John Zaborszky

1. *Decoupled Control.* In true large systems, like the power systems, the entire system composition may not be known or it may be too large to be considered in toto. Decoupled methods are needed which can operate in the absence of such systemwide information (in contrast to decentralized systems which imply coordination and knowledge of the total system.) On-line stabilization of a power system is an example.
2. **Priority Order Controls.** In very large systems under time pressure the selection of an optimal set of controls (perhaps thousands of them) may be impractical. One way out may be priority solving of the controls in advance, then the selection may be a one-cutoff-parameter. Emergency control of the large power system may be an example.

3. **“Textured” Systems.** Systems which have elements with close interaction on the short range but the interaction dropping off fast with the distance in such a way that no subsystems can be identified beyond the basic system element, yet all arbitrarily cut and overlapping "local" groups have strong interactions within themselves producing a texture rather than a structure (which would imply well defined interconnecting subsystems.) Reactive power flow in power systems is an example.
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