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Polysystems Analysis Corp.

PO Box 846, Huntington, NY 11743

A MATHEMATICAL MODEL OF A UTILITY FIRM

EXECUTIVE SUMMARY

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ABSTRACT

Utility companies are in the predicament of having to make forecasts, and draw up plans, whose horizons lie increasingly further in the future, and they must do so in an increasingly fluid and volatile socio-economic environment. Existing techniques are recognized as being inadequate. Their failing appears to be due to an inadequate understanding of the economic and behavioral processes that take place within a firm, and without it. The project that is being reported on here is to contribute to such an understanding.

Several lines of inquiry were pursued, all intended to lead to mathematical models for these processes. The models were to be well founded conceptually, technically sound, and compatible with the uncertainties that are inherent in any description of behavioral phenomena.

Three main topics are treated. One is the representation of the characteristics of the members of an organization, to the extent to which characteristics seem pertinent to the processes of interest. The second is the appropriate management of the processes of change by an organization. The third deals with the competitive striving towards an economic equilibrium among the members of a society in the large, on the theory that this process might be modeled in a way which is similar to the one for the intra-organizational ones.

Substantial areas of new ground had to be broken as the work progressed, conceptually as well as technically, and considerable difficulties of a mathematical nature had to be overcome, in order to attain the desired results. Additional theoretical as well as empirical work is indicated before the work can be applied to practice.

1. PROJECT GOALS AND OBJECTIVES

Utility firms are presently in the predicament of having to plan their development over ten or more years into the future. Moreover they must do so in spite of the accelerating pace with which events occur in the environment in which they operate and within their own organizations as well. It is highly desirable, therefore, that their planning be done as well as possible.

Unfortunately, planning and forecasting is not well done at present by business firms in general, as has been documented in several studies (by Hogarth, Einhorn, and others). An effort is under way (reported in a recent issue of the EPRI Journal) to improve the practices among utility firms but it is based on the same body of extrapolative techniques as a number of earlier undertakings with similar objectives. It is, therefore, unlikely to be much more successful than its predecessors.

The main shortcoming of these efforts may be their failure to start from a quantitative understanding of the economic, social, and socio-psychological processes that can take place within a firm, and without it, as well as a clear appreciation of how much of such an understanding is possible and of what the extent is of the uncertainties that remain.

Such an understanding admittedly does not exist at present. This report describes a project based on the supposition that such an understanding is indeed needed.

The goal of the project was to provide some of it.

The work proceeded in two directions. The major effort was expended on gaining quantitative insights into the internal functioning of an organization such as a utility firm; the other (and lesser one) on attaining similar insights into the processes that take place in its socio-economic environment. Both lines of inquiry had their origins in existing work. The one on the internal operations is based on a mathematical approach to organization theory by one of the contributors to this project, the other on the massive research on economic equilibrium theory. The effort in both studies reported here concentrated on achieving an understanding of the nature of certain dynamical processes, i.e., of the temporal evolution of the variables characterizing the functioning of an organization on one hand, and of a society in the large on the other.

The word "quantitative" in the preceding paragraph should not be construed as meaning "numerical." Numerical studies in the fields of this project invariably imply the gathering of empirical data, and that was definitely not an objective here. On the contrary, the results that were aimed for can be interpreted as defining the data that should be collected in the first place, and how the inevitable incompleteness and inaccuracy of those data would have to be dealt with. Both questions will need to be answered if the theory is to be validated and applied.

2. SUBJECT AREAS OF INVESTIGATION

As has just been mentioned, two main lines of investigation were pursued in this project, one aimed primarily at an understanding of the dynamic processes that evolve within an organization such as a business firm, and the other at the same kind of processes outside it. The first line itself soon divided into two principal branch lines. The second, however, proceeded very much along a single track, at least up to the point to which it was pursued.

The dynamic processes within an organization are governed by basically two determinants. One is made up of the pertinent characteristics of the members, the other is the manner in which organizational changes are managed. The two branch lines just mentioned are thus concerned with these two subjects. The studies of both are pervaded by a recurrent theme, namely the problem of how to treat the many uncertainties that are inherent in subjects that involve human behavior and societal events.

The bifurcations of the work on organization developed because it had become clear that an understanding of organizational functioning presupposed another, namely that of the relevant characteristics of organization members. The study of these characteristics thus constituted a major subject area of investigation. Relatively little of it could draw on earlier work and even in some of that, the realizations gained during this project induced major

revisions. Some benefit was derived in this line of work from the writings of sociologists, and from some of the data collected by experimental psychologists. By and large, however, new ground had to be broken in almost every direction. In fact, not even an adequate framework of terminology was found to be available for some of the pertinent characteristics of an organization member.

It developed that an essential distinction existed between those characteristics. Some, called "primary" in this project, are the direct determinants of a person's functioning in an organization. They are the ones that would be equally pertinent if the person were to be replaced by a machine. They are (speaking rather roughly)

- his efficiency, i.e., the time required by him on the average for the execution of his organizational tasks
- his fallibility, i.e., a quantity which measures the likelihood of his executing those tasks in the desired fashion
- his adaptability, i.e., the promptness with which he adjusts to the need to execute old tasks differently or new tasks altogether.

(The masculine pronouns here, and below, are used as a matter of convenience of expression.)

This list of the primary characteristics of an organization member is probably not complete but it bears out the remark just made, namely that a machine in his place

would have similar characteristics. In fact, it is the "secondary" characteristics, much more than the primary ones, that distinguish man and machine.

Among those secondary characteristics, an important distinction appears necessary, also. Some are found to be pertinent to a person's functioning in a job in the long run. These are of a socio-psychological nature. The second type of characteristics, by contrast, is psycho-physical. It is pertinent in situations, such as emergency management in a control room, in which information must be absorbed and acted upon at very high rates.

There are many of the socio-psychological characteristics. Some are displayed by individuals, others by groups. In this project, only individual characteristics were studied and more particularly some which were expected to have an important effect on the functioning of an organization as a whole. They were the following.

- Personal preferences, i.e., the fact that people have preferences among the tasks they are expected to do and that these affect their performances, i.e., their primary characteristics.
- Desire for autonomy, i.e., the fact that people perform better under arrangements which give them some latitude in the choice of their tasks and in the way they are done.
- Motivation, i.e., the fact that the performance of people can be turned to the better by certain

rewards of a pecuniary (or equivalent) nature.

Concepts such as these will seem rather vague and not well suited to any unarguable mathematical treatment. Arguments are, in fact, desired. In order to encourage them, the treatment given to these subjects has been axiomatic. In other words, it is based on what seem to be the fewest and most fundamental assumptions that lead to mathematical constructs with the properties one would wish to attach to concepts, such as those listed above.

The personal characteristics that are of significance in a high-pressure, high data rate environment are of a different nature altogether. People apparently have the facility of adapting their information processing capacity to the statistics of their inputs. Frequently occurring pieces of information tend to be processed more rapidly than others. In this way they manage to avoid information overload which otherwise might be inevitable. This adaptation capability was also the subject of investigation under this project.

The second main branch of the inquiry into the internal dynamics of organization, according to the distinction made up above, was concerned with management of change. The distinction is fundamental. Member characteristics are nonnegotiable. The same is true of the various events within a firm, or without it, that induce the requirement for change in the first place. The negotiable part is the organizational response to the requirement. In system

theory this is a process called "control," a term that was adopted also in the project under discussion.

The study of organizational control developed along two lines of its own. One of these was concerned with what might be called "optimizing" control of operational procedures. The idea is that a decline has been detected in the performance of an individual or group. It is to be corrected by a change in the procedures followed by the unit, in a direction which ultimately re-establishes optimal performance. This is to be done with due regard to the member characteristics and with a control procedure of the feedback type (in order to exploit the robustness of such procedures against uncertainties).

Such a procedure was developed. The development was carried out in three stages:

- A theory was established for a special type of nonlinear programming problem, called "multilinear," which is particularly appropriate to organizational problems.
- This type of problem was shown to be equivalent to a certain many-person game and a solution procedure was derived for it which has the desired feedback feature.
- The solution procedure was applied to a variety of procedural control problems.

The second approach to the development of control procedures was aimed at those which are representative of

planning in a firm, especially during periods of major internal or external change. The procedures are designed to be executed over a definite limited period of time, and to negotiate an optimal transition from the initial state of the firm in stages to the final one. The plan for this transition is to be drawn up assuming that it must be valid in the presence of major uncertainties, the latter formulated non-stochastically.

The theory was developed for the solution of such planning problems, and illustrated by several potential applications, notably one for planning by a utility firm. In this area of investigation more particularly,

- a theory was developed for the solution of planning problems in the presence of (set-valued) uncertainties, using dynamic programming on infinite-dimensional spaces;
- the computational solution by approximation was studied;
- the application of the theory to several problems in practice, especially to utility planning, was explored.

In the areas of investigation outlined here so far, the work was concerned with dynamic processes taking place within an organization. In the one remaining area, it was concerned with processes evolving outside. The incentive for this line of inquiry was twofold. On one hand a better understanding of the latter processes would patently entail

better planning. On the other, there was reason to hope that the mathematics developed for the internal processes might be applicable also to some external ones as well.

This conjecture has been borne out. There is a process that presumably takes place in a free society and which can, perhaps even does, evolve in basically the same way as the control procedures in an organization. This is the search among the members of such a society for an economic equilibrium.

The work in this area concentrated on the following issues

- A re-formulation of conventional equilibrium theory in terms of commodities, all of which are available only in certain indivisible units.
- The formulation in game-theoretical terms of the concept of an equilibrium in such an economy and a discussion of the existence question.
- The demonstration that the search for such an equilibrium can follow procedures which are similar to the control schemes in an organization. In particular, they include indications of futility in cases of non-existence of an equilibrium.

Perhaps more important than these results, however, was the realization that the search for an equilibrium is hardly the only dynamic process that takes place in a society. There are other, at least equally important ones, that evolve at the same time. These have remained uninvestigated

in this project. Indications are, however, that the methodology developed for organizational problems will be partly transferable to the societal ones.

3. FINDINGS AND RESULTS

Under this project, a theory was to be developed describing the dynamic process within and without an organization such as a utility firm. The principal findings and results were the following.

3.1 General Conclusions

Work on this project represents an advance into what is essentially virgin territory in the field of system theory, namely, the mathematical theory of systems consisting partly or wholly of human beings. Almost all of the work was new conceptually, and some of it required methodological innovation as well. On the other hand no evidence was uncovered supporting contentions which are sometimes heard, namely that mathematics of an entirely novel kind might be necessary for the description of such systems. Although methodological innovations were found to be needed, and others still seem desirable, no requirement is indicated for radical departures from existing techniques.

3.2 Primary Characteristics of Organization Members

As explained above, the primary characteristics of an organization member are the main determinants of his functioning in a firm. One of these (his) "efficiency") has been investigated earlier. Emphasis during this project was on two others.

Member fallibility. It was shown that the error probabilities of a "loyal" organization member, operating under routine conditions, are likely to have a special

property ("double stochasticity"). This result was derived from a single axiom which states, very roughly speaking, that such a member will tend to avoid large and costly errors. Existing mathematical theory on inequalities and majorization was used to obtain this result.

Member adaptability. It was shown that a person's reluctance, or inability, to adapt instantaneously to changes in his routine are likely to be characterized by a matrix difference equation. This result was derived from two axioms. The first states, roughly, that if a person's job is simplified for him, this simplification will not be reversed by his adaptation process. The second axiom is another "loyalty axiom." It states that a typical organization member who already operates in the desired way will not change his mode of operation when told that it is in fact desirable. The derivation extended (and corrected) some earlier work on stochastic learning theory.

3.3 Secondary Socio-Psychological Member Characteristics

Secondary characteristics affect a member's performance by way of his primary ones. The socio-psychological ones among them are considered to have significant effect in the long run. One characteristic, namely that of a person's having personal preferences among assigned tasks, required merely an adaptation of existing work in the field of economic utility theory. Two others were studied in this project.

Desire for autonomy. This characteristic expresses an

observed fact, namely that people perform better if they are given some latitude in the choice of their tasks or of the manner in which they carry them out. The mathematical formulation of this notion relies on three axioms which imply the existence of a quantity, the "degree of (an organization member's) autonomy"; and one additional axiom which determines the effect on his performance. Utility theory over abstract spaces was modified in order to be able to obtain these results.

Motivation. In sociological parlance, motivation is a catch-all concept roughly equivalent to the term "secondary socio-psychological" characteristics used here. In the present context, it is, however, used in a narrower sense. It refers merely to the effect on an organization member's performance of incentives of a financial or equivalent kind. Four axioms are stated which seem to reflect current understanding of the effect. It is shown that this understanding is incomplete.

Secondary Information-Processing Characteristics

Human beings involved in tasks that require the processing of information at high rates exhibit unusual capabilities which enable them to stave off the onset of overload. They apparently can adjust their cognitive procedures so that frequently occurring inputs are processed more promptly than others. They are thus "adaptive" processors. The following topics were investigated.

Overload condition. A condition was derived under which such a processor can, or cannot avoid overload. It is a generalization of one known for some time from queuing theory. The new version was established using the theory of non-stationary stochastic processes. As a by-product, several coding theorems were derived for such processes which constitute substantial generalizations of those of information theory.

Adaptations mechanisms. A study was made of the possible cognitive mechanisms that can explain the observed adaptation capability of human information processors. The best postulate apparently is that the resolution of detail received in the information is progressively sacrificed in favor of promptness in processing, as overload conditions are approached.

Experimental evidence. Comparison with psycho-physical data indicates that the postulated form of adaptation can explain observed behavior and that it in fact is the only satisfactory explanation that is so far available.

3.4 Organizational Dynamics

The dynamical processes that take place in a firm, i.e., those which follow a reasonably predictable evolutionary pattern, have two types of determinants. One type is made up of some of the members' personal characteristics. Those have just been discussed. The other is the manner in which organizational change is managed. In this project two approaches were studied to the latter. One was aimed at

establishing ways in which changes can be managed in the operational routine of an organization unit. The second dealt with the optimal planning of a transition from one mode of operation to another. Three of the topical areas discussed below are related to the first approach, the fourth describes optimal planning.

Multilinear Programming Theory. Many problems in the optimal operation of an organization can be formulated as non-linear programming problems of a special kind, called "multilinear" in this project. They are generalizations of the well-known linear programming problems of operations research, but the generalization is of a kind that has not been studied so far. A new duality theory was derived for it, based on general concepts from mathematical programming theory. A novel solution procedure was developed which resembles the widely used Simplex algorithm.

Many Person Games. The Simplex-like solution algorithm is unattractive in the context of organizational dynamics, however, essentially because it is not dynamic. In order to derive one that is, an equivalence was established between multilinear programming problems and certain types of multi-person games. A dynamic procedure for the solution of these games was shown to be convergent to the desired solution, under what appear to be fairly broad conditions. Some notions and techniques from game theory were helpful in this work but most of it covered new ground.

Organizational applications

The procedure derived in this way was applied to the controlled change in the operational practices of an organization such as the functioning of the line division of a firm, the interaction between an autonomy-minded executive and his staff, and the overcoming of the resistance to change among employees. Work done under this project on member characteristics was utilized. No precedents in the mathematical literature were found applicable.

Planning Under Uncertainty. A variable is "uncertain," in the interpretation given the term in this project, if its value is known only to lie in some interval or, more generally, in some set. A plan under these conditions is a program for keeping the performance variables of a firm within, or as close as possible to, certain target sets. The problem of generating such a plan was shown in this project to be a dynamic programming problem, but one with unusual features. For one, it is defined on an infinite-dimensional space. For another it must take into account, ahead of time, information that will become available only as the plan evolves. Approximation schemes for the computational execution of such plans were studied. Applications to several problems, including that of utility planning were developed. The methodology for this approach is largely new.

3.5 Equilibrium Theory

The notion of an economic equilibrium is over two-hundred years old. According to it the prices within an

economy will continuously adjust themselves until the demand for all goods is reduced to the level of their supply. In this way the members of the economy can satisfy all of their preferences within the constraints of their budgets. An existence proof for such equilibria which is general enough to be generally acceptable was given only recently. No model that is equally acceptable exists for the process of price adjustment. Yet, for planning purposes, such a model would be much more useful than any assurances of the existence of an equilibrium. The work on equilibrium theory during this project was based on the conjecture that the dynamics of intra-organizational processes might be similar to that governing the search for an equilibrium in an economy in the large.

Discrete economies. In order to develop the desired parallel with organization theory, equilibrium theory had to be first re-formulated in terms of goods which are available in indivisible units (only). Equilibria in such economies are most naturally based on game-theoretical concepts, i.e., as the results of competitive strivings among individuals or coalitions of individuals. Evidence was adduced during this project that such equilibria may not exist.

Dynamical Processes. The process equivalent to the price adjustment in a discrete economy is that of coalition formation and of subsequent income distribution. It was shown that both can evolve in ways very similar to the adjustments of intra-organizational operations. This result

confirmed the conjecture on which this part of the project was based.

General observation. Contrary to earlier expectations, the processes of coalition formation and income distribution cannot by themselves account for all important features of the evolutionary events in a society. Supplemental studies on a massive scale would be needed to explore the other processes that evidently evolve concurrently with those studied in the project and which are at least equally important.

4. IMPORTANCE OF RESULTS

The importance of the work under this project may lie in the following:

By all present indications, a comprehensive and mathematically satisfactory theory can be developed which describes the functioning of a system of human beings.

The mathematical apparatus necessary for this theory draws on system theory, operations research, mathematical economics, and the analytic tools normally used in these fields, augmented by perhaps a larger than usual injection from applied abstract analysis.

The theory points to specific areas and phenomena which will have to be empirically explored if the data are to become available for applications to practice.

5. APPLICATIONS WITHIN THE ELECTRIC POWER INDUSTRY

The project was aimed at gaining an understanding of certain processes which would contribute to better planning by the utility industry. Such an understanding seems to have been achieved, at least in regard to some of the intra-organizational processes. No fundamental obstacles are foreseen to a more complete understanding of these processes or of those taking place in a society at large. One can thus expect that the ultimate objective of better planning can be achieved as well.

The transition, however, from a basic research project, such as this, to an application in practice is a non-trivial undertaking. It is likely that another project of roughly the same duration and at least twice the budget would be needed to effect even only part of it. The budget would support the work of a research-oriented group, such as the investigators in the present project, in collaboration with personnel from an experienced management consulting firm. This collaboration would be necessary to reduce to practice the results that have been obtained already and to initiate research on others for which the need has not yet been recognized.

6. FUTURE RESEARCH DIRECTIONS

The work in this project is viewed somewhat like a bridgehead in a large, and largely unexplored area, namely a theory of systems that consist of human beings.

Opportunities for further research seem unlimited. Some that are implied by the work already done are as follows:

Organization theory--member characteristics

Among the primary member characteristics, more research is needed on both of those reviewed above (fallibility and adaptability). Empirical verification is desirable of the theory, as well as of its limitations. Additional theory is needed as well. Thus it is not known whether all of the results obtained for the properties of the primary characteristics remain valid under the effect of some of the secondary ones. Another primary characteristic is completely unexplored. This is the effect of memory organization and memory limitation on the performance of an organization member.

Of the secondary characteristics, the theory seems complete for only two (personal preference and desire for autonomy). Empirical verification is highly desirable for the second one. The theory of motivation even to the extent to which it is reported here is incomplete. Empirical evidence exists but is inconclusive.

Among the secondary characteristics that were not studied the greatest need is in the area of group characteristics. It is known that a person's performance in

an organization is determined at least as strongly by those around him as by him-(her-)self. Some work of a mathematical nature exists in the field but it is not part of a comprehensive approach.

Organization theory--collective characteristics

The theory derived in this project for the management of controlled change, by either of the two approaches, is in need of empirical verification, and probably also of modification by a collaborative undertaking described above.

Additional theory is, however, likely to be needed as well. The management procedures derived so far take into account the characteristics of individual organization members but not those of groups. It is conjectured that considerable practical benefits could be derived from an understanding of what allowances should be made for group characteristics.

Societal Dynamics

A general conclusion of the work on economic equilibrium theory, as pointed out above, was that the dynamic processes that take place in a society are not only economic and perhaps not even principally economic. Economists are aware of that. Yet they seem to be inseparably attached to their notion of man as a supremely rational being, with unlimited information, and information processing capacity. No major break with tradition seems to be in the making. What is needed, so to speak, is the replacement in the theory of homo economicus with one of homo sapiens. That, however, is a large undertaking.