SYSTEM DYNAMICS:

PORTRAYING BOUNDED RATIONALITY

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ABSTRACT

This paper examines the linkages between system dynamics and the Carnegie school in their treatment of human decision making. It is argued that the structure of system dynamics models implicitly assumes bounded rationality in decision making and that recognition of this assumption would aid system dynamicists in model construction and in communication to other social science disciplines. The paper begins by examining Simon's "Principle of Bounded Rationality" which draws attention to the cognitive limitations on the information gathering and processing powers of human decision makers. Forrester's "Market Growth Model" is used to illustrate the central theme that system dynamics models are portrayals of bounded rationality. Close examination of the model reveals that the information content of decision functions is limited and that the information is processed through simple rules of thumb. In the final part of the paper there is a discussion of the implications of Carnegie philosophy for system dynamics, as it affects communication, model structuring and analysis, and future research.

INTRODUCTION

The field of system dynamics has long been viewed by its practitioners as a discipline which is distinct from other major methodologies dealing with industrial and social systems. In particular, a distinction is drawn between system dynamics and the dominant conceptual framework offered by economics and operations research. However, to those outside the field, system dynamics is often regarded as nothing more than a rather specialized form of simulation modeling which belongs in the general tool kit available to management scientists.

Part of the reason for the persistence of these divergent viewpoints has been the inability of the system dynamics community to express its differences in modeling philosophy in a language that is understandable to those outside the field. There are of course exceptions to this general statement, for example, in the work of Meadows [1] and Andersen [2]. This paper adds a new dimension to that work. Its purpose is to draw attention to the fact that there is a widely recognized school of thought with a philosophy to social system modeling that has striking parallels to the underlying philosophy of system dynamics. This school of thought offers a language and set of concepts that may greatly improve our ability to communicate with other fields, and develop a stronger internal sense of the contribution that system dynamics can make to the analysis of social systems.

The school of thought is known generically as the Carnegie School, in recognition of the institution where much of the pioneering work was done in the 1950s and 1960s. A common and powerful theme underlying the work of the Carnegie School is the notion that there are severe limitations on the information processing and computational abilities of human decision makers. As a result, decision making can never achieve the ideal of perfect (objective) rationality, but is destined to a lower level of intended rationality. The Carnegie School contends that the behavior of complex organizations can only be understood by taking into account the psychological and cognitive limitations of its human members. Such a viewpoint focuses attention on the flow of information in a complex system, the quantity and quality of information that is amenable to human judgmental processing, and the form of decision rules used to represent judgments. It is at this most fundamental level of information flow and processing that strong parallels with system dyanmics can be found. It is also at exactly the same fundamental level that the Carnegie School departs radically from the traditional views of economics and operations research. [3]

In the main body of the paper, I will develop the ties between the Carnegie School and system dynamics. In doing so, it is not my intention to create the impression that the two fields are the same--they most certainly are not. Rather, they share some philosophy in common, philosophy that the Carnegie School has made explicit in its writings and that in system dynamics has always been implicit. The development begins with a more careful look at the "principle of bounded rationality", which is the cornerstone of Carnegie philosophy. Next, the structure and behavior of Forrester's "Market Growth Model" [4] is interpreted in the light of the principle of bounded rationality, leading to the major conclusion that system dynamics models are attempts to portray and unravel the consequences of bounded rationality. Finally, there is a discussion of the implications of Carnegie philosophy for system dynamics, as it affects communication, model structuring and analysis, and future research.

BOUNDED RATIONALITY

The Principle of Bounded Rationality

The principle of bounded rationality was formulated by Simon as the basis for understanding human behavior in complex systems. The principle recognizes that there are severe limitations on the thinking and reasoning power of the human mind. If we wish to predict the behavior of human decision makers within the context of the systems in which they work and live, it is first necessary to take account of their psychological properties.

Simon has defined the principle of bounded rationality in the following way: [5]

> "The capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problems whose solution is required for objectively rational behavior in the real world or even for a reasonable approximation to such objective rationality."

The principle of bounded rationality provides a basis for the construction of a theory of organizational behavior. [6] In Simon's words: [6]

> "Organization theory is centrally concerned with identifying and studying those limits to the achievement of goals that are, in fact, limitations on the flexibility and adaptability of goal striving individuals and groups of individuals themselves."

The principle of bounded rationality suggests that the performance and success of an organization is governed not by the anonymous interplay of market forces, but rather by the psychological limitations of its members: the amount of information they can acquire and retain, and their ability to process that information in a meaningful way. These limitations in their own turn are not physiological and fixed, they depend on the organizational setting within which decision making takes place.

Bounded Rationality and Organizational Decision Making

The principle of bounded rationality leads one to expect that organizations will undertake decision making in such a way as to greatly simplify the information processing and computational load placed on the human decision makers it contains. The pioneering work of Cyert and March [7] indicated that decision making in real business firms is indeed much simpler than one would anticipate based on classical models that assume objectively rational behavior. In the following section, we will draw on the work of Cyert and March to identify a number of empirical features of organizational decision making that can be interpreted as consequences of the principle of bounded rationality. We will consider such things as organizational goal structure and the information collection and processing habits of human decision makers. Our ultimate purpose is to show that many of these features are implicit in the structure and policy formulations of a system dynamics model.

1. Factored Decision Making

Common experience with human organizations will reveal that decision making responsibility is factored or parceled out among a variety of subunits. For example, many business firms adopt a functional structure that divides decision making between marketing, production, pricing, finance, labor management, etc. Cyert and March point to a "division of labor" in decision making. The decision problems that an organization must solve are so complex that they cannot be handled by an individual. Separable pieces of decision making are assigned to organizational subunits in the form of subgoals. Each subunit is charged with the responsibility of meeting its own subgoal and thereby contributing to the broader objectives of the organization. Of course this scheme will work perfectly only if there is no inherent conflict in goals - something which cannot be guaranteed when subunits are interdependent. Nevertheless, factored decision making is a necessary feature of a complex organization, and it goes hand in hand with a multigoal structure. Factoring simplifies decision making, but at the cost of focusing the attention of subunits narrowly on performance relative to the subunit goal.

2. Partial and Certain Information

Decisions are made on the basis of relatively few sources of information that are readily available, and low in uncertainty. While the above statement is not a direct quote from the Carnegie School, it can be inferred from comments that are made about the way that information is obtained and processed by an organization. Empirical observations of decision making in organizations indicate that decision makers seek only a

small proportion of the information that might be considered relevant to full consideration of a given situation. Their search for information tends to be conditioned by a focus upon problem symptoms and by a desire to avoid the use of information that is high in uncertainty. Both these tendencies in information selection favor the use of local feedback information reflecting current conditions in the immediate operating environment of a subunit, rather than information gathered more widely whose impact upon the subunit can be only vaguely conjectured. Both Cyert and March, and Simon, comment on the frequency with which such local feedback information is used rather than more global information required for "optimal" decision making.

3. Rules of Thumb

The organization uses standard operating procedures or rules of thumb to make and implement choices. In the short run, these procedures do not change, and represent the accumulated learning embodied in the factored decision making of the organization. Rules of thumb need employ only small amounts of information of the kind that would be made available through local feedback channels. Rules of thumb process information in a straightforward manner, recognizing the computational limits of normal human decision makers under pressure of time.

Consider, for example, the pricing decision of a business firm. Microeconomic theory would suggest that pricing decisions result from a sophisticated profit maximizing computation which equates marginal cost and marginal revenue. In fact, there is evidence to suggest that computationally simpler markup pricing is common. Under this method, average variable cost is taken as a base and is increased by a fractional markup to obtain the selling price. The markup is a rule of thumb which is heavily influenced by past tradition and by feedback information on profit, return on investment, market share, etc. (For an example of rule of thumb pricing, see Mass [8], pp. 31-36.)

BOUNDED RATIONALITY IN A SYSTEM DYNAMICS MODEL

In this section we will take an existing system dynamics model and interpret its structure and behavior in the light of the principle of bounded rationality. The model selected is based on Forrester [9] and describes the policies governing the growth of sales and production capacity in a new product market. Forrester's original model resulted from a case study of an electronics manufacturer, and represents the opinions of senior management of the company about the way that corporate growth is managed. We will first discuss the structure of the model and show how it embodies the organizational features of factored decision making, partial information and rules of thumb. We will then show, using simulation runs of the model, how the bounded rationality of organizational subunits can cause problems in market growth.

Factored Decision Making in the Market Growth Model

In common with the Carnegie School view, the market growth model can be broken down into a number of organizational subunits each of which is responsible for a part of the decision making that produces growth in the system as a whole.

Figure 1 depicts an organization with decision making factored into four subunits. In subunit 1 on the right of the figure, customers make their ordering decisions. Ordering is influenced by the number of customer contacts made by the marketing department and by customers' perceptions of the delivery delay in obtaining the product. In subunit 2 the marketing department makes decisions on the hiring of marketing personnel. An upper limit on marketing personnel is set by a marketing budget which moves in proportion to sales volume. Hiring adjusts personnel to this budgetary limit. In subunit 3 the firm makes decision on order filling. The rate of order filling depends on the available production capacity and its intensity of utilization. Finally, in subunit 4, the firm makes decisions on capacity management. Additional capacity is ordered whenever high delivery delay indicates there is a capacity shortage.

Partial Information and Rules of Thumb

In this section, we will consider in more detail the decision rules for capacity management, marketing, and customer ordering to illustrate examples of rules of thumb and the use of partial and certain information.

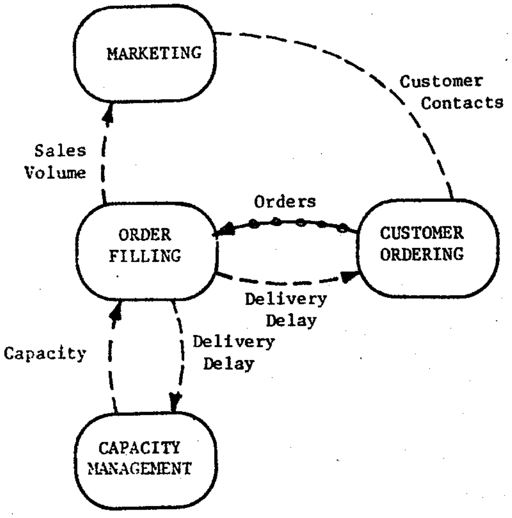

Figure 1. Organizational Subunits in the Market Growth Model

1. Capacity Management

Capacity management is represented as a two-stage decision making process involving first the detection of capacity shortage and then the ordering of capacity to eliminate the shortage. During the analysis the reader should bear in mind that the basic objective of capacity management is to adjust capacity to a level that will support demand. One could readily visualize a "rational" decision function in which future expectations of demand are generated across the lead time of capacity, and the expectations are used to drive capacity ordering. As we shall see, the decision making process that is actually used is computationally simpler and requires far less information. Let us first look at the equations for the detection of capacity shortage:

$$DDC(t) = DDRC(t)/DDOG(t) \qquad (1)$$

$$DDRC(t) = DDRC(t_0) + \int_{t_0}^{t} \frac{(B(t)/OFR(t)) - DDRC(t)}{TDDRC}\, dt \qquad (2)$$

$$DDOG(t) = DDT(t)*DDW + DDMG*(1-DDW) \qquad (3)$$

$$DDT(t) = DDT(t_0) + \int_{t_0}^{t} \frac{DDRC(t) - DDT(t)}{TDDT}\, dt \qquad (4)$$

In equation (1), delivery delay condition is an index of capacity shortage based on the ratio of delivery delay recognized by company DDRC to delivery delay operating goal DDOG. When DDC is greater than 1, a capacity shortage exists since it is not possible to fill orders at a rate that will keep delivery delay equal to the operating goal. Equation (2) states that DDRC is an exponential average of the ratio of backlog B to order fill rate OFR. [10] Equations (3) and (4) model the delivery delay operating goal as an adaptive goal based on a weighted average of a fixed delivery delay management goal DDMG and delivery delay tradition DDT which reflects past performance. Delivery delay tradition is formulated as an exponential average of recent delivery delay DDRC.

Consider now the cognitive and information processing assumptions of equations (1-4). The way the company recognizes the need to expand capacity is by making a judgment on delivery delay condition. The judgment requires a comparison of current delivery delay to the operating goal.

Current delivery delay is known from information on backlog and order fill rate which is readily available from concrete operating data, and therefore low in uncertainty. There is no need to go outside the company to do elaborate market surveys and project future demand expectations. If demand is growing, it will be reflected in a rising backlog. Thus, in equations (1) and (2), we see a clear use of partial and certain information. Furthermore, in equation (1), the information is processed in a simple rule of thumb that compares current delivery performance to an operating goal. In equations (3) and (4) the operating goal itself is seen to be a rule of thumb which adjusts to past traditions of performance. In conclusion, we see that the entire process of detecting capacity shortage uses only backlog and order filling information processed on the basis of simple judgmental criteria.

Now let us consider capacity ordering which is represented by equations (5-7) below.

$$\mathrm{COR}\ (t) = C(t)*\mathrm{CEF}(t) \qquad (5)$$

$$C(t) = C(t_0) + \int_{t_0}^{t} \mathrm{CAR}(t)\ dt \qquad (6)$$

$$\mathrm{CEF}(t) = f(\mathrm{DDC}(t))\ f(1) = 0,\ f'>0,\ f''>0 \qquad (7)$$

Equation (5) states that capacity ordering rate COR is the product of capacity C and capacity expansion fraction CEF. Thus capacity ordering takes place by a fractional expansion of existing capacity. Existing capacity in equation (5) is simply the integral of capacity arrival rate CAR (assuming no capacity discards). Equation (7) states that capacity expansion fraction CEF is an increasing nonlinear function of delivery delay condition, DDC. When DDC is equal to 1, the function takes a value of zero indicating there is no pressure to expand capacity because delivery delay is in line with the operating goal. As DDC increases above 1, the function becomes positive resulting in capacity expansion in equation (5). The function in equation (7) has a second derivative greater than zero indicating more aggressive ordering as rising DDC indicates a more serious capacity shortage.

Again, consider the cognitive and information processing assumptions of equations (5-7). The most striking feature of the equations is that nowhere is there an explicit attempt to compute the capacity needed to support demand. Capacity ordering is a rule of thumb that responds to "pressure" from delivery delay condition signaling capacity shortage. Delivery delay condition is the only information entering the ordering decision. There is no information from the market or from the marketing subunit. A policy of fractional expansion is computationally simple--a judgmental process that causes capacity to change in the right direction, but without the need to compute capacity requirements.

2. Marketing Expansion

Marketing expansion involves a two-stage decision making process of budgeting and hiring.

Consider first budgeting as represented by equations (8) and (9) below.

$$\mathrm{BM}(t) = \mathrm{AOFR}(t)*\mathrm{PO}*\mathrm{FBM} \qquad (8)$$

$$\mathrm{AOFR}(t) = \mathrm{AOFR}(t_0) + \int_{t_0}^{t} \frac{\mathrm{OFR}(t) - \mathrm{AOFR}(t)\ dt}{\mathrm{TAOFR}} \qquad (9)$$

The budget to marketing BM is defined as the product of average order fill rate AOFR, price of output PO, and fraction of budget to marketing FBM. The average order fill rate is defined in equation (9) as an exponential average of current order fill rate OFR. Together equations (8) and (9) represent a simple budgeting process in which a fixed fraction FBM of the total budget AOFR*PO is allocated to marketing.

The hiring of marketing personnel is represented by equations (10-12).

$$MP(t) = MP(t_0) + \int_{t_0}^{t} PH(t)\ dt \tag{10}$$

$$PH(t) = (IMP(t) - MP(t))\ /TAMP \tag{11}$$

$$IMP(t) = BM(t)/MS \tag{12}$$

In equation (10) marketing personnel MP is defined as the integral of personel hiring PH. In equation (11) personnel hiring is formulated as a goal adjustment process which eliminates the discrepancy between indicated marketing personnel IMP and marketing personnel MP over a time period TAMP, time to adjust marketing personnel. Finally, in equation (12), IMP is defined as the personnel that can be supported at a marketing salary MS by a budget BM.

Consider now the information processing assumptions of equations (8-12). Budgeting is a simple rule of thumb involving a fixed fractional allocation to marketing. Such a "frozen" budgetary process is computationally simpler for an organization than one in which allocation fractions are derived from a zero base. Hiring is a goal adjustment process. It uses only information that is specific to the marketing subunit: the current level of marketing personnel MP, and the authorized target IMP. Hiring does not include information about capacity or the delivery delay operating goal of the organization, both of which could conceivably be of relevance in a "fully informed" hiring decision.

3. Customer Ordering

An important feature of the market growth model is that customer ordering is entirely endogenously generated. The initiative for growth rests with the company. The company must contact customers in the market and persuade them to buy the product. Customer ordering (here called the product order rate POR) is represented by equations (13-16) below.

$$POR(t) = CC(t)*EPA(t) \tag{13}$$

$$CC(t) = MP(t)*NCR \tag{14}$$

$$EPA(t) = f(DDRM(t)) \quad f'<0\ . \tag{15}$$

$$DDRm(t) = DDRM(t_0) + \int_{t_0}^{t} \frac{DDRC(t) - DDRM(t)}{TDDRM}\ dt \tag{16}$$

In equation (13) product order rate POR is formulated as the product of customer contacts CC and effect of product attractiveness EPA (we assume that each contact can generate no more than one order). Thus a customer will order only if contacted, and only then if the product seems attractive. In equation (14), customer contacts are expressed as a fixed multiple NCR of marketing personnel MP. NCR, the normal contact rate, represents the average number of contacts made by marketing personnel during a month. In equation (15), the effect of product attractiveness EPA is formulated as a decreasing nonlinear function of delivery delay recognized by the market DDRM. Customers are assumed to be sensitive to delivery delay: they will be discouraged from ordering as delivery delay grows. In equation (16), DDRM is formulated as an exponential average of delivery delay recognized by the company DDRC, to represent the customers' perception of delivery delay.

Consider the information processing assumptions of equations (13-16). Customers need only two pieces of information to make their decision: they need to be made aware of the product and they need to judge its delivery delay. They need to know nothing at all about the detailed condition of the company (such as its marketing and capacity plans). Even their knowledge of delivery delay is local to the market and need not be the same as actual delivery delay the company is currently achieving.

We have now completed our review of the major decision functions in the model. We have shown that the formulations can readily be interpreted in the light of the principle of bounded rationality. Decision making is factored into subunits each striving for separate goals: marketing is striving for a personnel goal dictated by the budget, capacity management is striving to maintain delivery delay at a value dictated by the delivery delay operating goal. All the decision functions use partial and certain information which is but a small fraction of the total available to describe the state of the system. There are numerous examples of rule of thumb decision making.

Bounded Rationality Underlies Problem Behavior

In this section, three simulation experiments will be presented to show how well-intentioned policies (intendedly rational) can lead to problem behavior in a complex organizational setting. We start by showing that our three policies for marketing, capacity expansion, and ordering are intendedly rational. In other words, they are capable of producing reasonable behavior when taken in isolation or in simple combination. A demonstration of intended rationality is important because it indicates that there is a rationale to support the existing policies. We then bring all three policies together in a "complex organizational system" and show that together they can fail to bring about market growth even though the marketing policy is striving for growth and there is no inherent limit to market size.

Experiment 1 - Interaction of Customer Ordering and Marketing

In Experiment 1, the interaction of customer ordering and marketing is examined in isolation from capacity constraints on order filling. With no capacity constraints, delivery delay is constant so product order rate POR in equation (13) is directly proportional to marketing personnel. Figure 2 shows a simulation run of the simplified system over a time period of 80 months. Product order rate and marketing personnel both display unlimited exponential growth. Expansion of marketing personnel leads to an increase in product order rate which in turn leads to an increase in the budget for marketing, thereby justifying further marketing expansion. Growth is limited only by the delays in personel hiring and by the sales

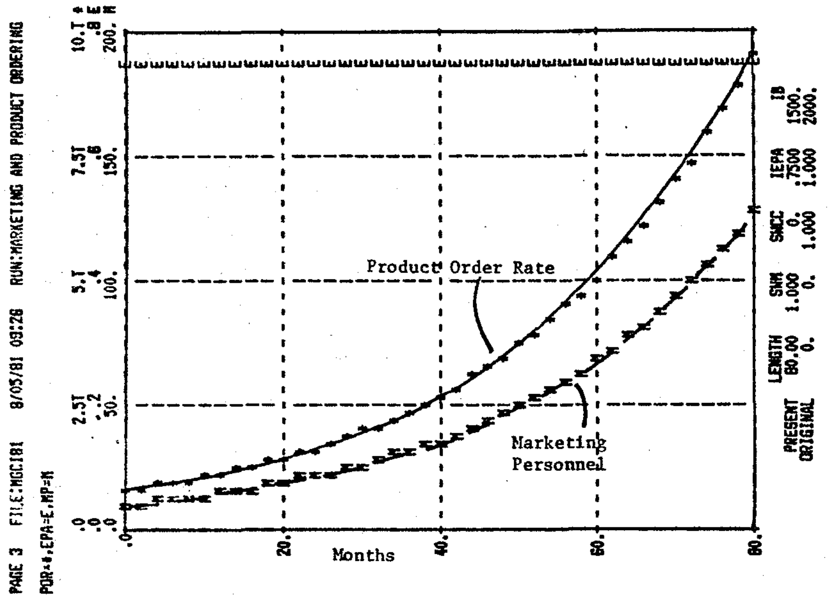

Figure 2. Marketing and Product Ordering with No Supply Constraints

efficiency of marketing personnel. We can interpret Figure 2 to mean that the marketing policy is intendedly rational in the sense that it is able to bring about market growth under conditions of perfect supply.

Experiment 2 - Capacity Expansion in Isolation

In Experiment 2, we look at the behavior of the capacity expansion policies in isolation from the market. We look at the simple question of

whether the capacity expansion policies are able to bring about an increase in supply in response to an exogenous increase in demand. We are therefore concerned not with how the demand increase is generated, but merely with the ability of capacity management to make a "rational response."

Figure 3 shows the results of a simulation run over a time period of 120 months. The run starts with the system in a state of equilibrium. Order fill rate is equal to the product order rate of 1000 units per month. Capacity is steady at 2000 units per month with a utilization of 50 percent. Delivery delay is equal to the operating goal which is set at two months. In the 10th month of the simulation, product order rate is increased by 50 percent. We trace the adjustment of the manufacturing system over time.

The simulation run shows that the demand change is smoothly accommodated. Shortly after the increase in product order rate, capacity utilization increases, thereby allowing order fill rate to rise before any permanent change in the level of capacity has taken place. By month 24, order fill rate is equal to product order rate, meaning that the demand increase has been satisfied. Rising delivery delay after week 10 begins to set in motion a long-term capacity adjustment. As we might expect, capacity rises only gradually, reflecting long delays in capacity acquisition and a reluctance to commit to expansion before there is solid evidence in terms of delivery delay to justify expansion. As capacity arrives in month 24, utilization and delivery delay gradually return to their starting values.

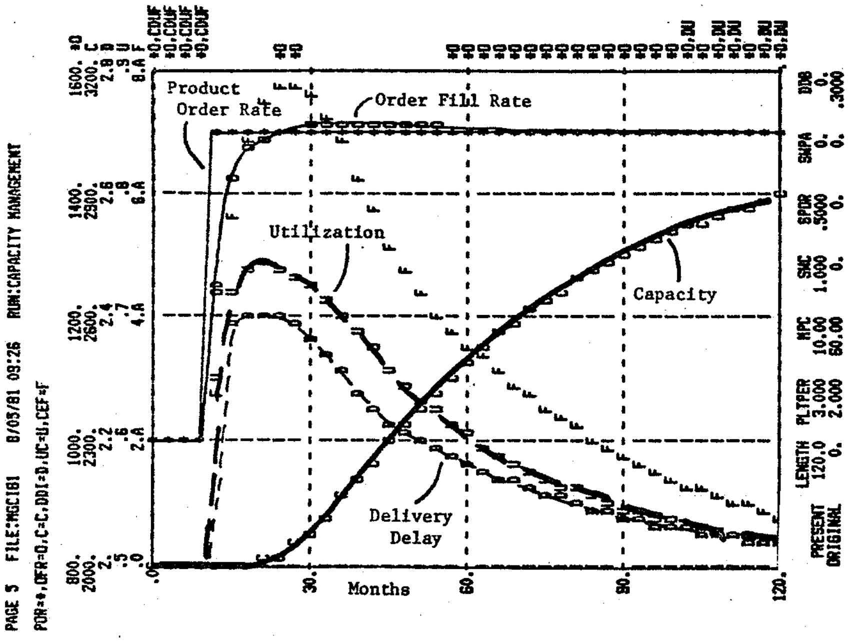

Figure 3. Capacity Management with Exogenous Product Order Rate.

We can interpret Figure 3 to mean that the capacity expansion policy of equations (1-7) is intendedly rational. It brings about a gradual expansion of capacity in response to reliable and conclusive delivery delay information, indicating that expansion is justified.

Experiment 3 - Bounded Rationality in a Complex System

In the final experiment we put all three policies together starting from the knowledge that the marketing policy can generate growth and that the capacity expansion policy can follow increases in demand. There is good reason to expect a system that will generate continual growth in orders and capacity. In fact, continual growth need not occur, and under extreme conditions, stagnation and decline can set in.

The final simulation run shows the extreme that results in decline. To appreciate this run, the precise conditions under which it was generated should first be described. Customer ordering and marketing perform according to exactly the same rules used in Experiment 1. Capacity expansion is slightly modified in two respects in relation to Experiment 2. First, delivery delay operating goal DDOG of equation (3) is made entirely a function of past tradition by setting delivery delay weight DDW equal to 1. In experiment 2 DDOG was equal to a fixed management goal DDMG. The change is a subtle one that in no way alters the apparent "logic" of the capacity management policy. A condition of excess delivery delay will still elicit capacity expansion, but continued failure to meet the operating goal will result in goal deterioration. Second, capacity expansion fraction CEF in equation (7) is modified to include a delivery delay bias DDB as shown below:

$$CEF(t) = f(DDC(t) - DDB) \quad f(1) = 0,\ f'>0,\ f''>0 \qquad (17)$$

In the modified equation DDB plays the role of a management attitude toward capacity expansion. When DDB is greater than 0, management has a conservative attitude toward capacity expansion, preferring initially to overcome

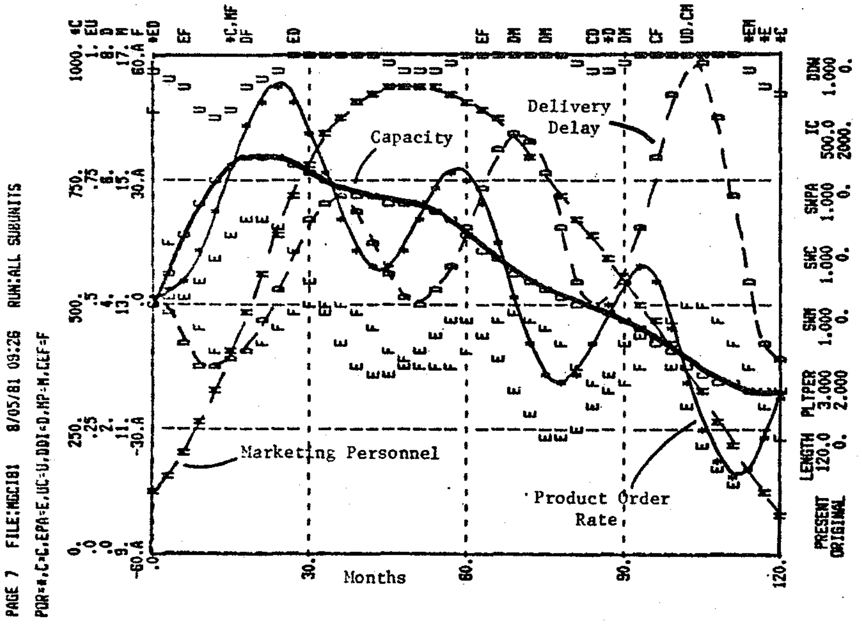

Figure 4. Interaction of Marketing, Product Ordering, and Capacity Management

supply shortages by increasing the utilization of capacity rather than ordering additional capacity. However, if delivery delay condition rises sufficiently high, capacity will be expanded in the "normal" way. Again, the underlying "logic" of the capacity ordering policy has not changed. Rising delivery delay will still elicit capacity expansion, but the evidence from delivery delay must be more compelling than in a case when DDB = 0.

Figure 4 shows the behavior of the complete market growth model over an interval of 120 months. The run starts from a condition in which delivery delay is 4 months--twice the initial operating goal, and a clear sign that capacity expansion is required (even with DDB = 0.3). Capacity expands for the first 18 months of the run. In addition, marketing personnel expand, bringing about a growth in product ordering. The initial pattern of growth is the one we might anticipate from the previous two experiments. However, beginning in month 18, growth in the system begins to falter, and eventually decline in both capacity and marketing personnel sets in. This behavior can be explained as a consequence of bounded rationality in both the capacity management and marketing policies. Capacity expansion requires convincing and solid evidence of capacity shortage in the form of high delivery delay--a requirement that is reasonable in isolation. High delivery delay depresses ordering and ultimately inhibits growth of the total budget. With a fixed budget allocation (that worked well in isolation) growth of marketing is restricted, thereby eliminating the primary driving force behind growth. The complete set of policies interact in a way that fails to bring forth the growth potential of the market. Failure arises because the consequences of a well-intended (intendedly rational) policy within one subunit radiates unintended effects elsewhere in the system. It is this failure due to unintended consequences that is the hallmark of bounded rationality.

To summarize, in this section we have tried to show how a system dynamics model can be interpreted in the light of the principle of bounded rationality. We have argued that the marketing, capacity expansion, and ordering policies of the "Market Growth Model" are formulated recognizing implicitly the information processing limitations of human decision makers. Using simulation runs, we have shown that the policies are intendedly rational: the marketing policies promote exponential growth and the capacity policies bring about a conservative adjustment of capacity to demand changes. We have also demonstrated with a final simulation run that intendedly rational policies can produce unintended consequences which are characteristic of bounded rationality. In the market growth model, the unintended consequences lead to market stagnation and decline.

IMPLICATIONS FOR SYSTEM DYNAMICS

The principle of bounded rationality is a powerful general law underlying all social systems. Its consequences have been studied and developed in the widely known literature of the Carnegie School. The principle is an implicit part of the structure of system dynamics models. These three statements strongly suggest that the ideas of the Carnegie School have some important implications for the field of system dynamics. As I see it, there are implications for the communication of the field to other social science disciplines, for the structuring and testing of system dynamics models, and for research on generic structures. Each of these themes will be developed in more detail below.

Improved Communication to Other Disciplines

System dynamics is not well understood or accepted outside the system dynamics community. Part of the reason for this lack of acceptance is that system dynamics models are not clearly differentiated from the other mathematical modeling methods of the social sciences such as economics and operations research. System dynamics often deals with areas of application similar to economics and operations research. When analysis yields results conflicting with the more conventional approaches, the discrepancy is often explained by appeals to the importance of a "feedback approach" or "systems philosophy," neither of which conveys much meaning to those outside the field. The Carnegie School offers a language in which the fundamental difference of system dynamics models is explained in terms of the models' treatment of information flow and information processing in decision making.

System dynamics models are built implicitly on the principle of bounded rationality. They portray the bounded rationality of human decision makers and human organizations. They show the distributed responsibility for decision making that is characteristic of real organizations. They contain multiple goals. They use local feedback information in decision making rather than sophisticated future expectations. Decision functions are portrayed as rules of thumb, requiring limited information input and limited computation of that information.

When we realize that system dynamics models are portraying bounded rationality, we can understand why they should be different to models of other dominant social science disciplines. Both operations research and microeconomics focus on portrayals of efficient and rational decision making. In contrast, system dynamics focuses on portrayals of bounded rationality, with the intention of identifying the information structures that are consistent with bounded rationality. Therefore, as a theory of decision making, system dynamics differs sharply from classical economics by assuming that non-rational behavior is both likely to occur and likely to be sustained over time. As a tool for normative analysis, system dynamics differs from classical optimization by setting out to explain why inefficiences exist and seeking decision functions that improve on existing behavior, rather than striving for optimal decision functions regardless of the existing decision making structure of the system.

Conceptualization--A Focus on the Organization

System dynamics offers a number of structuring principles [11] to guide model formulation. These principles are of most value when the boundary of the model has already been set and the major interacting elements already identified. There is very little guidance for the earliest and sometimes most challenging step of initial conceptualization. What features of a situation make it suitable for analysis with system dynamics? Are there patterns of structure that one can anticipate in the construction of a system dynamics model?

The process of conceptualization would be greatly aided if we clearly recognized that we are building models of human organizations and that those organizations are governed by the principle of bounded rationality. [12] We could then anticipate both the general form and specific structural features of a model.

In general form, system dynamics models are likely to portray a depth of organizational structure. They will involve multiple sectors or subunits with divided decision making responsibility. It is within the complex structure of a multisector system that bounded rationality is most likely to produce major problems in overall system behavior. Problems that are posed within the setting of a single organizational subunit are unlikely to be suitable for analysis with system dynamics.

Specifically, we would expect decision making within subunits to reflect the limits of human rationality. Thus, it is extremely unlikely that a decision function in a given subunit will be gathering large quantities of information from distant parts of the organization. Decision functions are likely to employ locally available information, and to process this information with simple rules of thumb. Where very complex formulations arise, there are grounds for questioning the complexity and seeing whether a more compact formulation can achieve the same basic intention. Decision functions should reflect the multi-goal feature of large organizations. Different subunits will be responsible for different goals and their decision making biased toward achieving those goals independent of their impact on overall system performance.

The observations above are indicative of the structuring aids that can be obtained from a Carnegie perspective. Much work could undoubtedly be done in this area building on the fine structure of decision making that has been described in Carnegie writing, but which is not covered in this paper. New structuring aids would complement, not contradict, the existing principles of formulation.

Behavior Analysis--Making Use of Intended Rationality

The analysis of system dynamics models is traditionally broken into partial and whole model tests. Partial model tests usually perform a purely technical function, enabling the modeler to eliminate formulation errors in a small model rather than unravel the same errors in the more complex setting of the complete model. The explanation of the behavior of the system is made in terms of whole model tests.

The Carnegie School approach to organizations suggests there may be powerful insights to be derived from contrasting partial and whole model tests. Partial model tests can be viewed as demonstrations of the intended rationality of decision making in organizational subunits. Partial model tests often reveal that the policies of a subunit make perfect sense when the subunit is free to act, independent of other organizational constraints. Whole model tests indicate how intendedly rational policies can break down and produce problem behavior in a sufficiently complex organizational setting. Contrasting partial and whole model tests, to show that rational policies can in fact produce problem behavior, is a powerful method of

generating understanding of complex system behavior. Understanding is created by building upon the intuitively clear behavior of a subunit or small group of subunits. As additional subunits are added, a clear explanation can be generated of why policies begin to fail in the more complex setting.

An example of the contrast of partial and whole model tests was presented earlier in the analysis of the market growth model. There partial model tests of the marketing and capacity management policies indicated reasonable behavior of the two policies taken in isolation. A full model test involving customer ordering, marketing, and capacity management revealed non-rational behavior in which the firm failed to grow when faced with a limitless market for its product.

Research on Generic Structures

The ideas of the Carnegie School are likely to be valuable in providing methodological support for the concept of generic structures. In common with other disciplines, system dynamics is seeking order and general structure in the social systems with which it is dealing. There is, of course, already a structure that is common to all system dynamics models. They all use the same basic building blocks of levels, physical flows, information flows, and decision functions. However, beyond the common rate level structure, the question remains whether there are larger groupings of basic building blocks that might occur repeatedly in social and economic systems. These larger groupings are described as generic structures.

To adopt a Carnegie School perspective, the question of whether generic structures exist is similar to the question of whether common forms of organization exist. The principle of bounded rationality tells us that organization should evolve around the cognitive limitations of its members. It is probable (though by no means certain) that common organizational structures have evolved to cope with these common and fundamental limitations of human decision makers. It is also probable that common problems are generated by these organizational structures.

The ideas of the Carnegie School lead us to a research method for finding generic structures and testing empirically whether they are indeed generic. Generic structures should be defined by the breakdown of different organizational subunits, by the channels of communication between subunits, and by the mental shortcuts embodied in rules of thumb for decision making. If in a particular application we observe a piece of structure that is responsible for problem behavior, we might then dissect the structure to ask whether it can be explained as a consequence of bounded rationality. What is it about the structure, and in particular the assumed complexity of the information network, that limits the rationality of decision making? What changes in the information network would be compatible with more rational decision making, and why do they not currently exist? Answers to questions like these could form the basis of a refutable empirical study of other organizations similar to the one that yielded the generic structure.

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[9] Forrester, J.W. "Market Growth as Influenced by Capital Investment." Sloan Management Review.

[10] For an example of how (2) reduces to an exponential average see Forrester, J.W. Industrial Dynamics, Appendix E, Cambridge, Massachusetts, M.I.T. Press, 1961.

[11] Forrester, J.W. Principles of Systems. Cambridge, Mass., M.I.T. Press, 1968.

[12] Models of biological and ecological systems have also been constructed. I am suggesting these be distinguished from social systems on the grounds that their principles of organization are not necessarily the same as social systems, and the principle of bounded rationality may not apply so strongly to them.

APPENDIX A

DYNAMO Listing of Market Growth Model

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TOF:
00010 NOTE  MARKET GROWTH AS INFLUENCED BY CAPITAL INVESTMENT
00020 NOTE  MGCI81 CREATED BY JOHN D.W. MORECROFT JULY 1981
00030 NOTE  FROM MGCI FOR  PAPER ENTITLED  SYSTEM DYNAMICS: PORTAYALS
00040 NOTE  OF BOUNDED RATIONALITY PRESENTED AT 1981 CONFERENCE
00050 NOTE  IN SYSTEM DYNAMICS RESEARCH
00060 NOTE  THE MODEL IS BASED ON  J.W. FORRESTER'S MARKET GROWTH MODEL
00070 NOTE  IN SLOAN MANAGEMENT REVIEW, VOL9, NO. 2, WINTER 1968, PP83-105
00080 NOTE
00090 NOTE  PRODUCTION CONTROL
00100 L B.K=B.J+(DT)(POR.JK-OFR.JK)
00110 N B=IB
00120 C IB=2000  UNITS
00130 R OFR.KL=PR.JK
00140 R PR.KL=C.K*UC.K*SWCC+((B.K/DDMG)*(1-SWCC))
00150 C SWCC=1
00160 NOTE  DELIVERY DELAY CONDITION
00170 A DDC.K=DDRC.K/DDOG.K
00180 L DDRC.K=DDRC.J+(DT/TDDRC)(DDI.J-DDRC.J)
00190 N DDRC=DDI
00200 C TDDRC=4  MONTHS
00210 A DDI.K=B.K/OFR.JK
00220 NOTE   DELIVERY STANDARDS
00230 A DDOG.K=(DDT.K)(DDW)+(DDMG)(DDWC)
00240 N DDWC=1-DDW
00250 C DDW=0
00260 C DDMG=2  MONTHS
00270 L DDT.K=DDT.J+(DT/TDDT)(DDRC.J-DDT.J)
00280 N DDT=DDMG
00290 C TDDT=12  MONTHS
00300 NOTE
00310 NOTE  CAPACITY MANAGEMENT AND SUPPLY
00320 L C.K=C.J+(DT)(CAR.JK)
00330 N C=IC
00340 C IC=2000  UNITS OF OUTPUT/MONTH
00350 R CAR.KL=DELAY3(COR.JK,LTC)
00360 C LTC=12  MONTHS
00370 L UOC.K=UOC.J+(DT)(COR.JK-CAR.JK)
00380 N UOC=COR*LTC
00390 R COR.KL=C.K*CEF.K*SWC
00400 C SWC=0
00410 A CEF.K=TABHL(TCEF,(DDC.K-DDB),0,2.5,.5)
00420 T TCEF=-.07/-.02/0/.02/.07/.15
00430 C DDB=.3
00440 NOTE  UTILIZATION OF CAPACITY
00450 A UC.K=TABHL(TUC,DDM.K,0,5,.5)
00460 T TUC=0/.25/.5/.67/.8/.87/.93/.95/.97/.98/1
00470 A DDM.K=B.K/C.K
00480 NOTE
00490 NOTE  MARKETING
00500 L MP.K=MP.J+(DT)(PH.JK)
00510 N MP=10  PEOPLE
00520 R PH.KL=(IMP.K-MP.K)/TAMP
00530 C TAMP=20  MONTHS
00540 A IMP.K=BM.K/MS
00550 C MS=4000  $/MONTH
00560 A BM.K=AOFR.K*PO*FBM
00570 L AOFR.K=AOFR.J+(DT/TAOFR)(OFR.JK-AOFR.J)
00580 N AOFR=OFR
00590 C TAOFR=1  MONTH
00600 C PO=960  $/UNIT
00610 C FBM=.1
00620 NOTE
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00630 NOTE  PRODUCT ORDERING
00640 R POR.KL=CC.K*EPA.K*OC*(1+STEP(SPOR,TSPOR))
00650 C OC=1  ORDER/CONTACT
00660 C SPOR=0/TSPOR=10
00670 A CC.K=(MP.K*SWM+MPC*(1-SWM))*NCR
00680 C SWM=0
00690 C MPC=60  PEOPLE
00700 C NCR=100  CONTACTS/PE00700 C NCR=100  CONTACTS/PERSON-MONTH
00710 A EPA.K=NEPA.K*SWPA+EEPA.K*(1-SWPA)
00720 C SWPA=0
00730 A NEPA.K=TABHL(TEPA,DDRM.K,0,10,1)
00740 T TEPA=1/.97/.87/.73/.53/.38/.25/.15/.08/.03/.02
00750 L DDRM.K=DDRM.J+(DT/TDDRM)(DDRC.J-DDRM.J)
00760 N DDRM=DDRC
00770 C TDDRM=6  MONTHS
00780 A EEPA.K=IEPA+STEP(SPA,TSPA)
00790 C IEPA=1
00800 C SPA=0
00810 C TSPA=36  MONTHS
00820 NOTE
00830 NOTE  CONTROL STATEMENTS
00840 PLOT POR=*,C=C/EPA=E,UC=U/DDI=D/MP=M/CEF=F
00850 PRINT POR,EPA,B,MP,OFR,DDRM,PH,C,DDOG,CEF
00860 SPEC DT=.5/LENGTH=0/PLTPER=2/PRTPER=0
00870 RUN COMPILE
00880 C LENGTH=80
00890 C SWM=1
00900 C SWCC=0
00910 C IEPA=.75
00920 C IB=1500
00930 PLOT POR=*/EPA=E/MP=M
00940 RUN MARKETING AND PRODUCT ORDERING
00950 C LENGTH=120
00960 C PLTPER=3
00970 C MPC=10
00980 C SWC=1
00990 C SPOR=.5
01000 C SWPA=0
01010 C DDB=0
01020 PLOT POR=*,OFR=O/C=C/DDI=D/UC=U/CEF=F
01030 RUN CAPACITY MANAGEMENT
01040 PLOT POR=*,C=C/EPA=E,UC=U/DDI=D/MP=M/CEF=F
01050 C LENGTH=120
01060 C PLTPER=3
01070 C SWM=1
01080 C SWC=1
01090 C SWPA=1
01100 C IC=500
01110 C DDW=1
01120 RUN ALL SUBUNITS
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APPENDIX B

DYNAMO List of Variable Names

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         MGCI81 DYNAMO                                      8/05/81

                           LIST OF VARIABLES

SYMBOL   T WHR-CMP   DEFINITION

ACFR     L   21      AVERAGE ORDER FILL RATE (UNITS/MONTH) <21>
         N   21.1
B        L    2      BACKLOG (UNITS) <2>
         N    2.1
BM       A   20      BUDGET TO MARKETING (DOLLARS/MONTH <20>
C        L   10      CAPACITY (UNITS OF OUTPUT/MONTH) <10>
         N   10.1
CAR      R   11      CAPACITY ARRIVAL RATE (UNITS OF OUTPUT/MONTH/
                      MONTH) <11>
CC       A   23      CUSTOMER CONTACTS (CONTACTS) <23>
CEF      A   14      CAPACITY EXPANSION FRACTION (FRACTION/MONTH) <14>
COR      R   13      CAPACITY ORDER RATE (UNITS OF OUTPUT/MONTH/
                      MONTH) <13>
DDB      C    5.1    DELIVERY DELAY BIAS (DIMENSIONLESS) <5>
DDC      A    5      DELIVERY DELAY CONDITION (DIMENSIONLESS) <5>
DDI      A    7      DELIVERY DELAY INDICATED (MONTHS) <7>
DDM      A   16      DELIVERY DELAY MINIMUM (MONTHS) <16>
DDMG     C    8.3    DELIVERY DELAY MANAGEMENT GOAL (MONTHS) <8>
DDOG     A    8      DELIVERY DELAY OPERATING GOAL (MONTHS) <8>
DDRC     L    6      DELIVERY DELAY RECOGNIZED BY COMPANY (MONTHS) <6>
         N    6.1
DDRM     L   26      DELIVERY DELAY RECOGNIZED BY MARKET (MONTHS) <26>
         N   26.1
DDT      L    9      DELIVERY DELAY TRADITION (MONTHS) <9>
         N    9.1
DDW      C    8.2    DELIVERY DELAY WEIGHT (DIMENSIONLESS) <8>
DDWC     N    8.1    DELIVERY DELAY WEIGHTING COMPLEMENT
                      (DIMENSIONLESS) <8>
DT       C   30
EEPA     A   27      EXPERIMENTAL EFFECT OF PRODUCT ATTRACTIVENESS
                      (DIMENSIONLESS) <27>
EPA      A   24      EFFECT OF PRODUCT ATTRACTIVENESS (DIMENSIONLESS)
                      <24>
FBM      C   21.4    FRACTION OF BUDGET TO MARKETING (DIMENSIONLESS)
                      <21>
IB       C    2.2    INITIAL BACKLOG (UNITS) <2>
IC       C   10.2    INITIAL CAPACITY (UNITS OF OUTPUT/MONTH) <10>
IEPA     C   27.1    INITIAL EFFECT OF PRODUCT ATTRACTIVENESS
                      (DIMENSIONLESSO <27>
IMP      A   19      INDICATED MARKETING PERSONNEL (PERSONS) <19>
LENGTH   C   30      LENGTH OF SIMULATION RUN (MONTHS) <30>
LTC      C   11.1    LEAD TIME FOR CAPACITY (MONTHS) <11>
MP       L   17      MARKETING PERSONNEL (PERSONS) <17>
         N   17.1
MPC      C   23.2    MARKETING PERSONNEL CONSTANT (PERSONS) <23>
MS       C   19.1    MARKETING SALARY (DOLLARS/PERSON-MONTH) <19>
NCR      C   23.3    NORMAL CONTACT RATE (CONTACTS/PERSON-MONTH) <23>
NEPA     A   25      NORMAL EFFECT OF PRODUCT ATTRACTIVENESS
                      (DIMENSIONLESS) <25>
OC       C   22.1    ORDERS PER CONTACT (ORDERS/CONTACT) <22>
OFR      R    3      ORDER FILL RATE (UNITS/MONTH) <3>
PH       R   18      PERSONNEL HIRING (PERSONS/MONTH) <18>
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         MGCI81 DYNAMO                                      8/05/81

PLTPER   C   30      PLOT PERIOD (MONTHS) <30>
PO       C   21.3    PRICE OF OUTPUT (DOLLARS/UNIT) <21>
POR      R   22      PRODUCT ORDER RATE (UNITS/MONTH) <22>
PR       R    4      PRODUCTION RATE (UNITS/MONTH) <4>
PRTPER   C   30      PRINT PERIOD (MONTHS) <30>
SPA      C   27.2    STEP IN PRODUCT ATTRACTIVENESS (DIMENSIONLESS)
                      <27>
SPOR     C   22.2    STEP IN PRODUCT ORDER RATE (DIMENSIONLESS) <22>
SWC      C   13.1    SWITCH FOR CAPACITY (DIMENSIONLESS) <13>
SWCC     C    4.1    SWITCH FOR CAPACITY CONSTRAINT (DIMENSIONLESS)
                      <4>
SWM      C   23.1    SWITCH FOR MARKETING (DIMENSIONLESS) <23>
SWPA     C   24.1    SWITCH FOR PRODUCT ATTRACTIVENESS
                      (DIMENSIONLESS) <24>
TAMP     C   18.1    TIME TO ADJUST MARKETING PERSONNEL (MONTHS) <18>
TAOFR    C   21.2    TIME TO AVERAGE ORDER FILL RATE (MONTHS) <21>
TCEF     T   14.1    TABLE FOR CAPACITY EXPANSION FRACTION
                      (DIMENSIONLESS) <14>
TDDRC    C    6.2    TIME FOR DDRC (MONTHS) <6>
TDDRM    C   26.2    TIME FOR DDRM (MONTHS) <26>
TDDT     C    9.2    TIME FOR DDT (MONTHS) <9>
TEPA     T   25.1    TABLE FOR EFFECT OF PRODUCT ATTRACTIVENESS
                      (DIMENSIONLESS) <25>
TSPA     C   27.3    TIME FOR STEP IN PRODUCT ATTRACTIVENESS <27>
TSPOR    C   22.2    TIME FOR STEP IN PRODUCT ORDER RATE (MONTHS) <22>
TUC      T   15.1    TABLE FOR UTILIZATION OF CAPACITY
                      (DIMENSIONLESS) <15>
UC       A   15      UTILIZATION OF CAPACITY (DIMENSIONLESS) <15>
UOC      L   12      UNFILLED ORDERS FOR CAPACITY (UNITS OF OUTPUT/
         N   12.1     MONTH) <12>
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