EXPERIMENTS ON AN ADAPTIVE COMPUTER MODEL OF A DISTRIBUTION CHANNEL

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Summary

The aim of the paper is to use computer simulation models of an entire industry's distribution channel as instruments of theory development. The major phenomena to be explained center around recent developments in distribution systems, resulting from advancing technology in the logistics of distribution as well as in communications between the various levels of the channel. Dynamic instabilities and various adaptive response patterns are found to be explainable more immediately by the hierarchical nature of the feedback-control relationships prevailing between various levels of the distribution channel than by environmental changes reflected in demand patterns.

I

This paper is addressed to two overall questions: (1) How far can some of the dynamic instabilities and adaptive patterns observed in real-world distribution channels be explained within an abstract computer simulation model? (2) Is a generalized hierarchical system adequate as explanator of these adaptive patterns, that is, are these instabilities mainly due to the hierarchical nature of communications- and goods- flows or are different classes of variables required to explain these phenomena?

The following phenomena were to be explained:

(1) The thrust towards integrated channels of distribution -- reflected in the development of modern supermarket chains -- as a result of the efforts aimed at eliminating differentials in the efficiency at various levels of the channel (Experiment 1)

(2) The effect of the adaptability of the ordering policy prevalent within a distribution channel (Experiment 2)

(3) The effect of improved communications within the channel on channel efficiency (Experiment 3)

(4) The impact of increased consumer awareness and higher activity in shopping, on the whole channel (Experiment 4)

The channel of distribution -- as a system of interaction of component parts -- is faced by an external environment consisting in the consumer sector. Variations in consumer demand therefore represent environmental change to which the system can adapt in various ways. Accordingly, four types of environmental change are brought to bear within the experiments: (a) constant level demand, (b) a one-time increase in demand, (c) a constantly increasing demand, and (d) a cyclically fluctuating demand. The consequences of each type of demand pattern on system behavior are investigated.

Finally, it was shown that an abstract or general "value-flow-model" can be used to assess these interactions just as the more specific and particular "unit-flow-model". (Experiment 5)

The approach and problem focus of the paper ran parallel to J. Forrester's pioneering work in "industrial dynamics".[1] While it draws inspiration therefrom, it differs in content, methods, and technique: It addresses itself to overall generalizations (if not "laws") pertaining to the adaptive behavior of entire industries rather than of firms; it represents a particular industry on the basis of differentials in the level of technology employed at the various levels of the distribution channel rather than the more detailed mechanics of a particular enterprise; and it employs FORTRAN rather than DYNAMO as the computer language for purposes of simulation. These differences make it, however, not neccesarily opposed to the spirit of "industrial dynamics"; in fact, it could be viewed as an extension thereof. No point is seen in entering into a further discussion of the merits or demerits of industrial dynamics.[2]

II

The computer model incorporates elements of what may be termed a "typical" channel of distribution, consisting of a manufacturer (labeled level E in the computer output plots of the Figures in the Appendix), two levels of wholesalers (levels D and C), one level repre-

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The computer programs were realized by Mr. Warren Brown (Michigan State University) who also made several substantive contributions.

senting the retailer (level B) and one level denoting the consumer (level A).

As the objective of the computer experiments was to study the adaptive behavior of the components of the channel as well as that of the total channel, that is inter-level behavior, intra-level phenomena such as competition and cooperation were abstracted from. This approach to modeling is derived from the economic tradition: The generalized channel may be viewed as an aggregate or an entire industry where the manufacturing level denotes all manufacturers producing a given product, the wholesaler levels all wholesalers performing a particular distributive function and so on.

The experiments were run for eighty simulated time periods.

The distribution channel is modeled as a sequence of feedback-control systems, that is, each level effects the levels above and/or below and is also being influenced by the same. Moreover, within each level the distributive process is seen as a process of "value-adding": The manufacturer transforms raw materials and uses the services of labor and capital, in order to produce a finished product. The wholesaler receives these products and provides "time, place, and possession" utilities; the same is true for the other level of wholesaler as well as the retailer. It can also be said of the consumer, in as far as the consumer performs activities prior to the actual consumption, such as traveling to the shop, selecting the product, transporting it to the home, and so on.

A major element in this model -- which makes it an adaptive model -- is found in learning process due to system operation over time: The forward transfer functions change with increasing levels of output, denoting the adoption of an improved organizational "technology". Technology can also be improved through investment of resources in new equipment.

Out of retained earnings, two types of adaptive responses could be made: (a) to increase the efficiency of the level of distributing goods, and (b) to increase consumer demand through promotion. Both actions -- just as the flow of goods and orders -- involve time-lags of various magnitudes.

Figure 1 provides a highly simplified schematic representation of the Value Flow Model, together with pertinent explanations, while Figure 2 depicts the corresponding flow chart with a more detailed explanation of variables.

III

In Experiment 1, a typical channel is depicted, where different levels of the system operate with different degrees of efficiency: For example, advances in manufacturing technology may proceed faster than advances in the technology of distribution, say, at the retailing level. When the various levels of the experimental variable -- consumer demand -- are brought to bear on such a system, a basic conclusion emerges: Irrespective of the specific demand pattern, a general increase in demand will only bring about as much increase in system performance, as the lowest level of technology employed within the hierarchy of system levels, permits.

(Figures 3a to 3c show, in highly simplified form, the output plots pertaining to (a) constant, (b) step-function (with a one-step change), and (c) linearly increasing demand).

This conclusion highlights the hierarchical properties of the distribution channel and illustrates the general notion that "a chain is as strong as its weakest link". There are therefore only two alternatives for improvement in performance open to any member of the distribution channel: (a) to help unilaterally the other members of the channel with the expectation that the improvement in overall system performance will more than compensate him for such an act; or (b) to acquire control over the entire channel, so that a most efficient allocation of resources can be attained. (In equilibrium, the productivity of each level of the distribution channel must be equalized if the final sales to the consumer are to be maximized). These conclusions provide a powerful explanation for the trend towards modern supermarket development: By integrating backwards, these modern retail outlets are able to apply a technology which leads to an even flow of goods through the channel.

In Experiment 2, the effect of alternative ordering policies on system performance was analyzed. When a relatively insensitive ordering policy was adopted, environmental change -- in the form of a one-time change in demand -- had little impact on the operation of the system. However, the adoption of a very sensitive ordering policy on the part of the two wholesale levels led to a more than appropriate response for both constant and a step-function demand pattern. This response in turn was "over-corrected" till finally both levels went through increasingly severe oscillations with secondary effects on the other levels: In other words, technological improvements within one aspect of system operation -- for example, ordering policy -- which are unaccompanied by changes in other activities -- such as inter-level communications -- lead to unstable systems, characterized by increasing oscillations. This type of "hunting behavior" is a familiar aspect of over-reactive systems in both the physical and social sciences. (See Figures 4a and 4b)

In Experiment 3, a technological change was depicted that consisted in the installation of an improved system of communications at all levels of the system; its main effect was the reduction in the time-lags of responses of one system-level to another. A cyclical demand pattern was brought to bear on the system. The consequences of this environmental change were different from the previous one: Reduction in delay time led to an almost instantaneous adaptation of the system at all levels to changes in demand. This led to a marked cyclical pattern at all levels of the distribution channel; the cycles had a roughly equal periodicity, a phase lag of almost zero, and an amplitude that differed mainly by the differences in value-added. (See Figure 5). Effective communications within the channel, by reducing time-lags of adaptation, lead to very prompt responses; when cyclical patterns are inherent in the environment, however, this will lead to the transmission of periodic "shocks" throughout the system.

In Experiment 4, the impact of changes in the role of consumers on system activity is depicted. Specifically, due to improved technology of shopping -- such as shopping by television, mail-order, and so on -- the relative distribution of effort within the channel changes. When the value added by the consumer level increases due to improved technology of shopping, the value added by the other levels must go down.

This result is evident from the adaptive pattern of the retail, wholesale, and manufacturing sectors. The consequences of such a change on the social system of the distribution channel may also be considered: Reduced activities at these levels would lead to reduced employment of the factors of production which then would be employed to a greater extent in the consumption-level. In other words, the average individual would spend less on "distributive-value-addition" and more on "consumptive-value-addition", thus reflecting a change from what may be termed a distributive to a consumptive channel of distribution. (Figure 6 shows this result in a very dramatic form).

Experiment 5 addressed itself to a methodological problem, that is, the problem of the adequacy of the more abstract Value Flow Model in depicting real-world-like phenomena. The level of abstraction contained in the forward transfer function -- denoting the value-adding process -- was reduced by the explicit representation of price-cost relationships and the flow of physical units through the channel. This made possible the inventory computations and the inter-level transfers in terms of "real-world" terminological entities. For the course of the experiment it was found that this model -- termed the Unit Flow Model -- exhibited properties of inter-level adaptation and overall systems response akin to those of the more abstract Value Flow Model.

The simplified flow chart of Unit Flow Model, together with explanations, is shown in Figure 7.

IV

It was demonstrated that a multi-level, feedback-control type of simulation model was adequate as explanator of many phenomena that have been associated with real-world distribution channels in the past, or are just making their appearance.

The most important insight gained through the simulation exercise may be summarized as follows: (a) the hierarchical nature of a distribution channel explains many of the dynamic instabilities observable in the real world while the demand pattern itself plays only an indirect role; (b) technological change, if applied "unevenly", can lead to severe instabilities within the system; (c) severe instabilities and/or differences in the level of technology applied at different levels appear to provide a powerful rationale for integrated channel operations; (d) improved order policies, or improved communications about environmental change, taken alone will lead to unstable patterns; only a combination of technological improvements in both activities will lead to overall improvements; (e) it is sometimes desirable to build responses into the system that are less effective than what existing technology permits, if the total system is to operate with a semblance of stability, and (f) in as far as the whole distribution channel may be viewed as a system for division of labor, any innovation that saves labor at one level, or leads to higher level of output for given inputs, will lead to an opposing shift in the activities of other levels of the system.

Methodologically it may be concluded therefore that some highly abstract models of hierarchical systems may in fact explain a large fraction in the variance of systemic variables. This conclusion should not be interpreted as a call for less "realism" in the formulation of computer models of distribution channels but for greater structural insights into their hierarchical properties. Computer simulation provides, however, a more facile instrument than pure analytic modeling as the number of interactions in real-world systems is very large indeed, and characterized by many nonlinearities in key relationships.

References

[1] Jay W. Forrester, Industrial Dynamics, M.I.T. Press, 1961.

[2] See article by J. Igor Ansoff and Dennis P. Slevin, "An Appreciation of Industrial Dynamics", Management Science, Vol. 14, No. 7, March, 1968, pp. 383-397, in which they define "...Industrial Dynamics as a simulation approach based on a view of the firm as a feedback system" (p. 394), and Jay W. Forrester, "Industrial Dynamics -- After the First Decade", Ibid., pp. 398-415.

ADDENDUM TO FIGURE 1:
SCHEMATIC FLOW CHART EXPLANATION

MATERIALS FLOW: the flow of one level's output (for one time period) to the next level's input (for the following time period).

INFORMATION FLOW: the communications process which allows one level to place an advance order with its supplier. This is the source of the time lag between primary demand and production at all levels.

INPUT: a measure of the goods used in the production process at each level. It is derived from the previous level's output.

OUTPUT: the result of the value-adding process of production or distribution determined by the forward transfer functions. Output passes on to become the input into the next lower level.

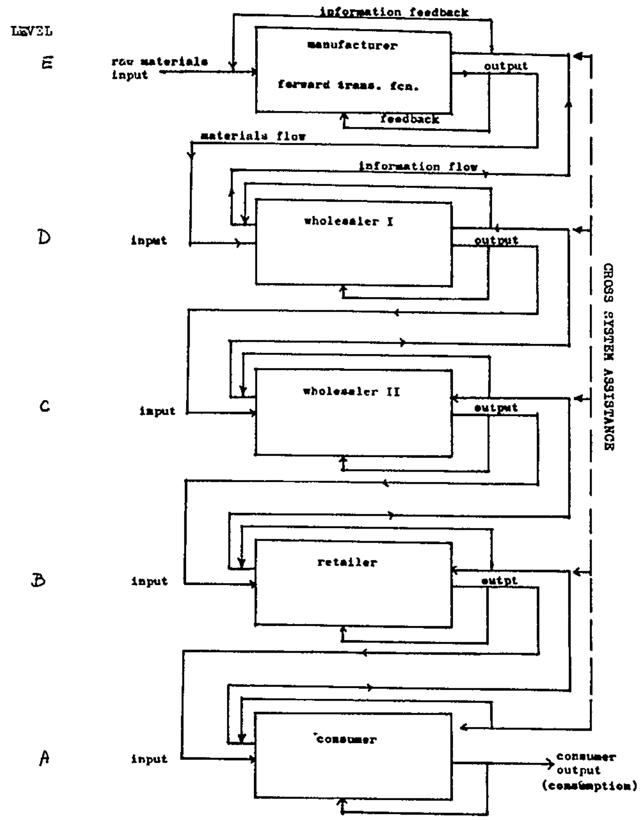
FORWARD TRANSFER FUNCTION: the scalar by which each level's inputs are multiplied to obtain the value added by it. This is analogous to the "markup" of a retailer or other channel member.

FEEDBACK FUNCTION: the improvement that a level can make in its efficiency through processes of "learning" which lead to a higher level of technology. Learning brings about increases in the forward transfer function only during a production increase.

INFORMATION FEEDBACK: a comparison of the next lower level's needs with the present capacity and input availability. It is used for adjusting orders and inventories.

CROSS SYSTEMS ASSISTANCE: the aid which one level may contribute to another level's production processes, with the aim of eliminating bottlenecks in the distribution system. The effect is to smooth flow of goods and to avoid large inventory buildups.

FIGURE I SCHEMATIC REPRESENTATION OF VALUE FLOW MODEL *



ADDENDUM TO FIGURE 2:
DEFINITION OF VARIABLES IN VALUE FLOW MODEL

PROFIT: measure of the profit potential as a function of the volume of production and the forward transfer function (production-efficiency) of each level.

RET: a measure of retained earnings which is derived from cumulative profits over time minus investments in increasing capacities of other "bottleneck" levels of the distribution channel.

PROD: the level of production for a level expressed as the input value plus a "value added" factor.

SUPP: the supply of goods available for sale (prod + inv).

INV: the inventory on hand at the beginning of a time period.

LEFT: the inventory on hand at the end of a time period (equals inv of the next period).

DEM: demand at consumer level for a particular time period.

INP: input used by a distribution level which is multiplied by the scalar (forward transfer function) to obtain prod.

X: the internal feedback which can increase the forward transfer function but never decrease it. (It represents learning behavior at each level of the channel).

FCN: forward transfer function which measures the value added to input to obtain output.

HOLD: the "safety inventory" which a level keeps on hand to protect against unexpected increases in demand.

AVAIL: the amount of input which is available for a level at a given time period. It is equivalent to the output of the next higher level from the previous time period. It places a maximum on a level's input.

ORDER: an estimate of the input which a level expects to require five time periods hence. This time-span also represents the time-delay factor in adjusting to variations in demand.

SOLD: the amount of output which is sold by a level at a period of time. It is equal to the next level's input for the next time period.

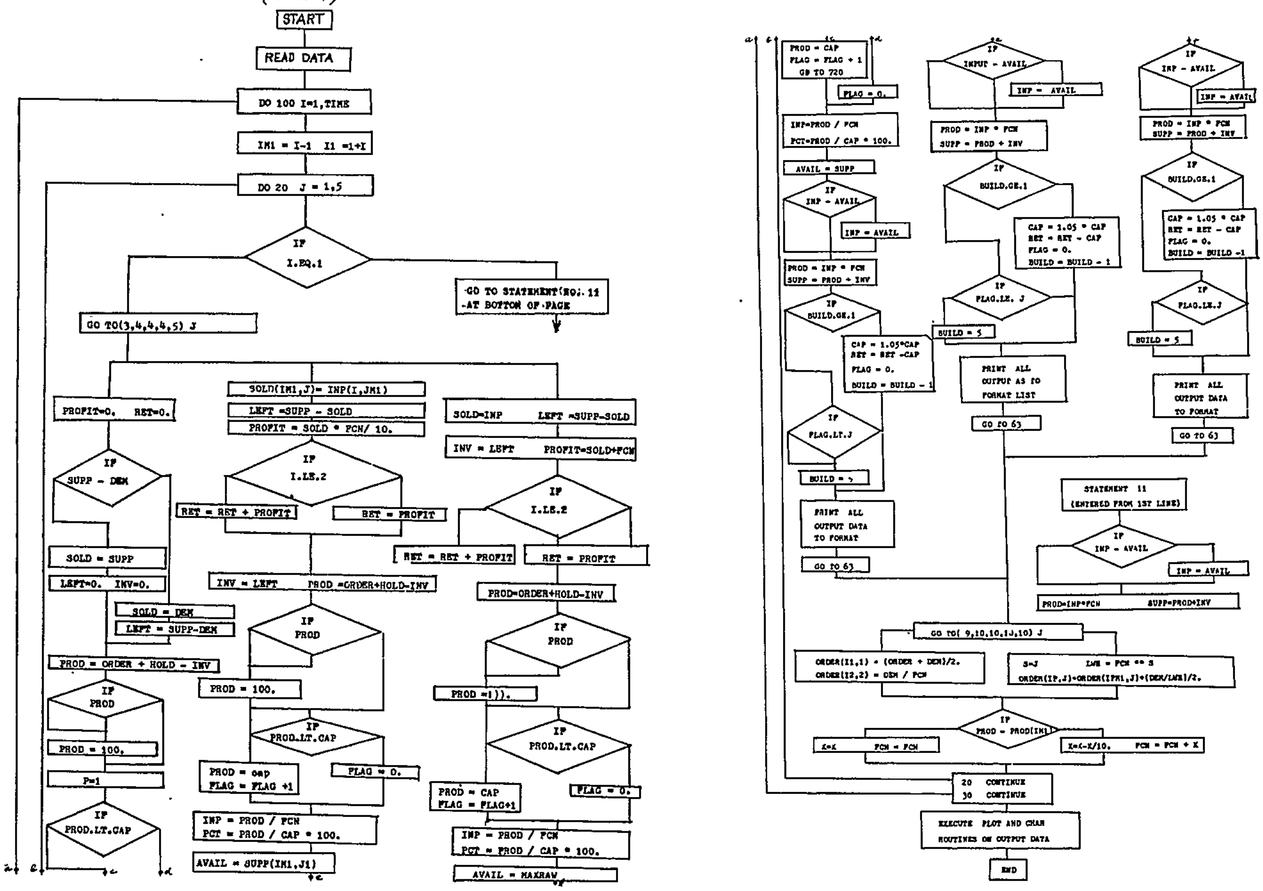
FLAG: an indicator which counts the number of periods that a level is operating at 100% capacity. It is used to indicate bottlenecks in the distribution system.

BUILD: the mechanism that brings about increases in the capacity of a level's production if it acts as a bottleneck in distribution in relationship to other channel levels.

CAP: the "capacity factor" which a level cannot physically exceed. Capacity can be increased by investment of retained earnings by the given level or by another level (which deems it in its best interest to free the channel of volume-retarding bottlenecks).

PCT: the percent of capacity at which a level is operating ("load factor").

FIGURE 2: FLOW CHART FOR VALUE FLOW MODEL (PART I)



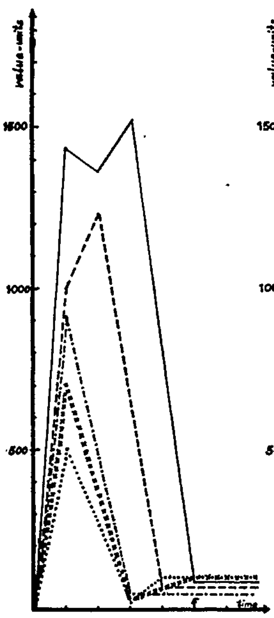


Figure 3a: Constant Demand

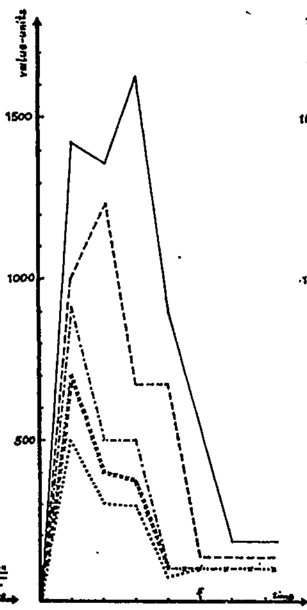


Figure 3b: Step-Function Demand

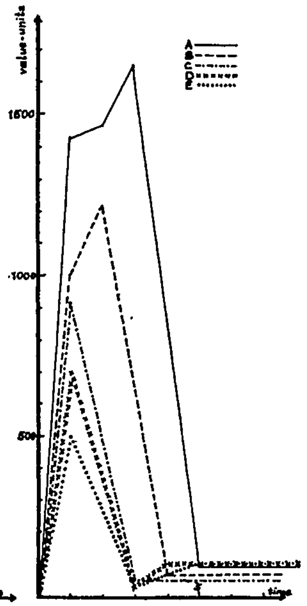


Figure 3c: Linear Increase in Demand

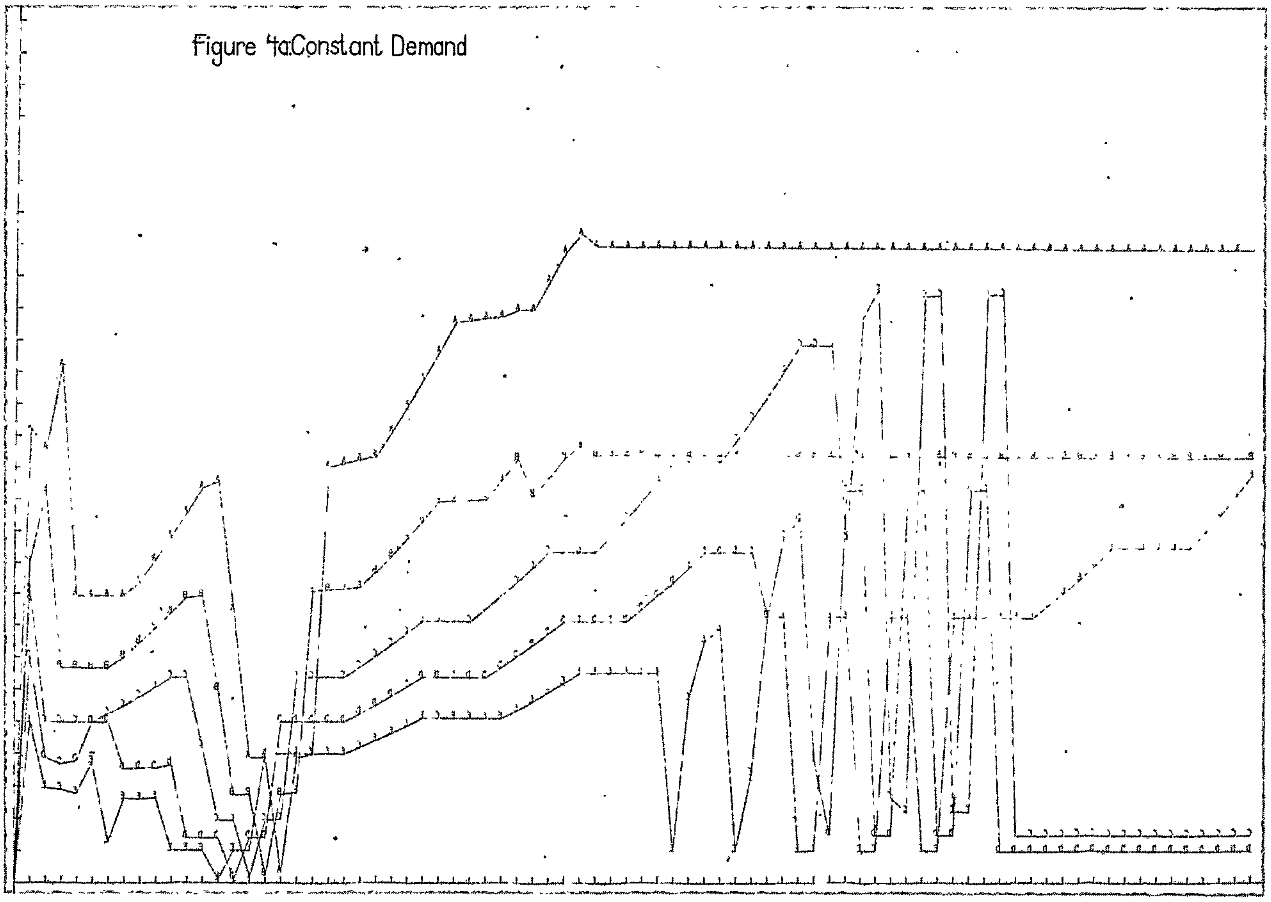


Figure 4a:Constant Demand

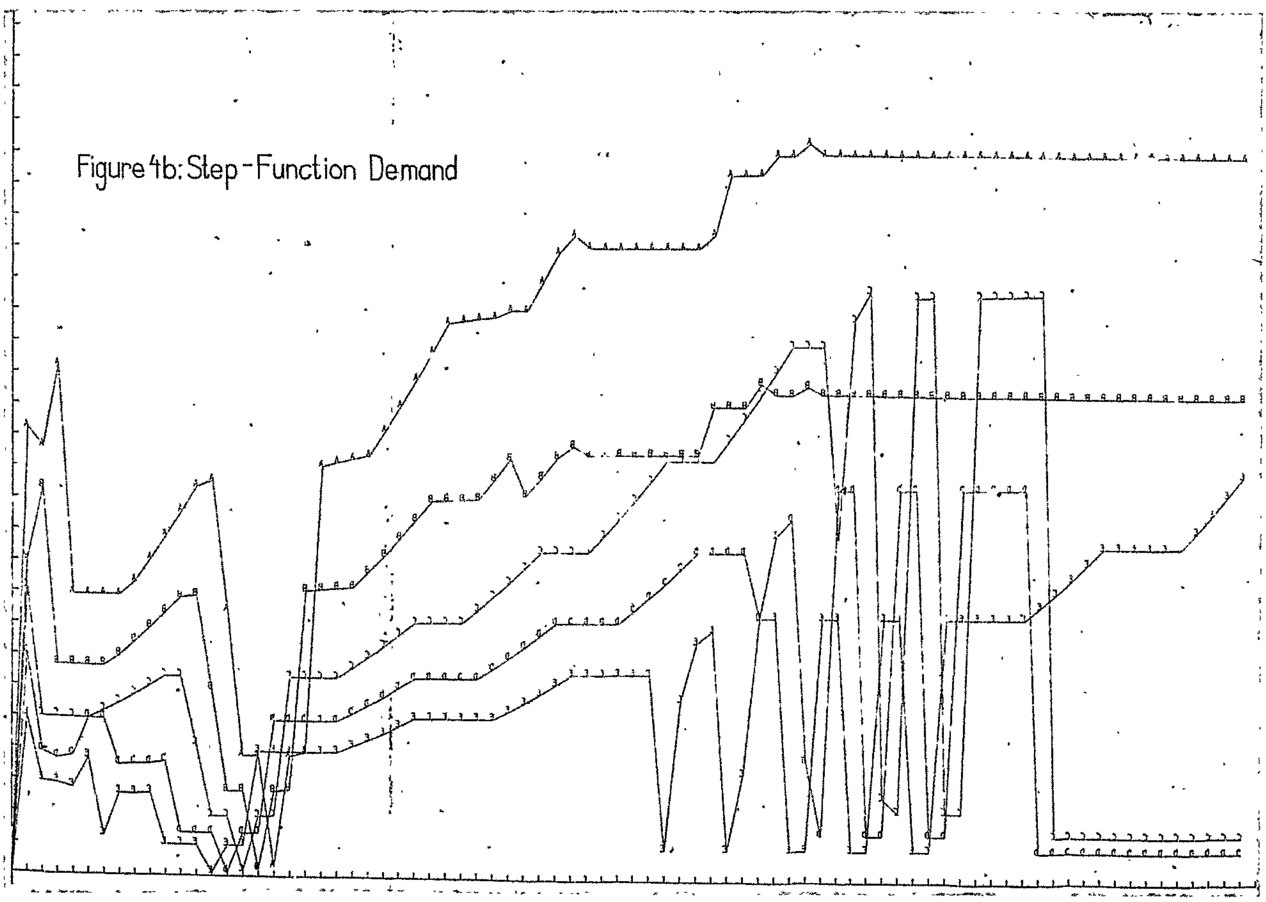


Figure 4b: Step-Function Demand

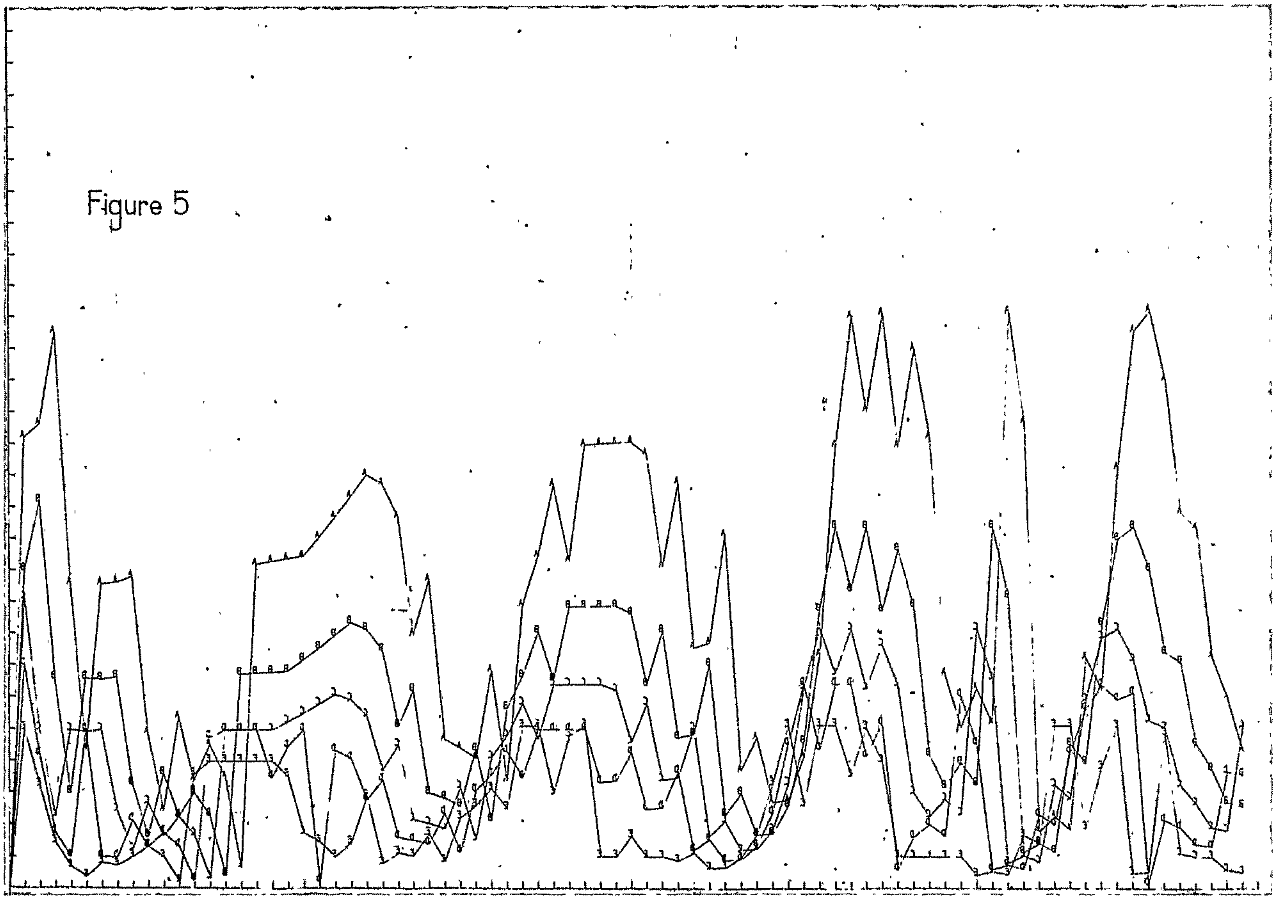


Figure 5

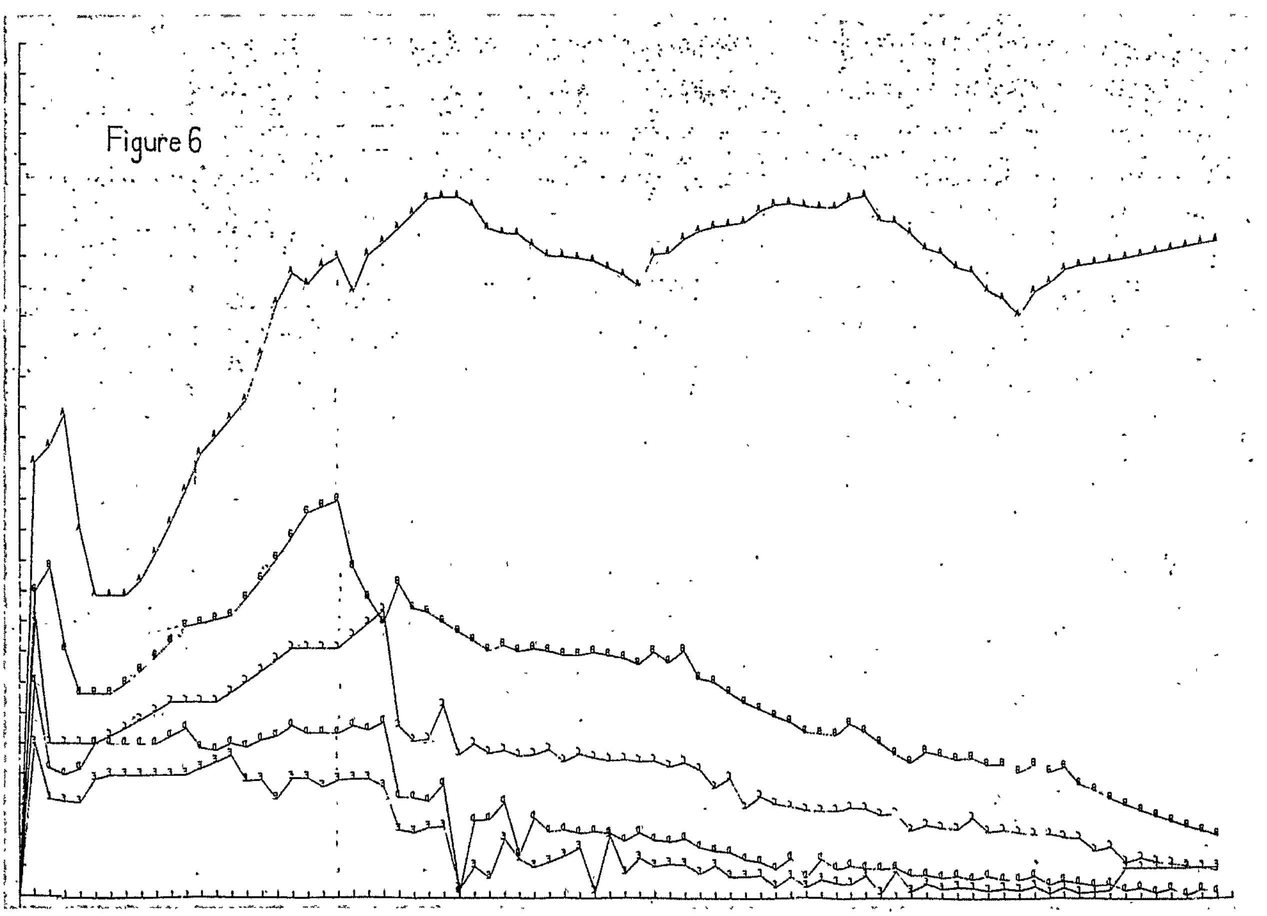


Figure 6

ADDENDUM TO FIGURE 7:
DEFINITION OF VARIABLES IN UNIT FLOW MODEL

PROFIT: total revenue minus total costs, expressed directly in monetary terms. Profit for a given level of the channel is realized at the end of each time period.

REV: the total revenue gained from sales of goods in a given time period. Arrived at by multiplying selling price times number of units sold in the given time period.

COST: the total costs of goods sold in a period including carrying costs (which a level has the ability to decrease over time). Total cost is arrived at by adding buying price times units bought and carrying rate times number of units on hand during the period.

RET: the cumulative sum over time of profits minus any costs incurred in expanding capacities or increasing demand through promotional expenditures.

PRICE: the selling price of a given level's output which can also be interpreted as the buying price of the next lower level's input.

RATE: the carrying cost of keeping a unit on hand for one period. Every unit is charged this cost at least once since it is assumed that each unit is kept on hand throughout the period and sold at the end. Units held in inventory are charged this cost for every subsequent unit of time.

FORSAL: the number of units which any given level has available for sale in a given time period. This equals the number purchased plus the number of units in inventory.

SOLD: the number of units sold by a level in a given time period. It also equals the number of units purchased by the next lower level during the following time period.

PURCH: the number of units purchased by a level during a given time period which is equal to the number sold by the next higher level during the previous time period.

INV: the number of units which a level has on hand after selling to the next lower level in the system. This then becomes the beginning inventory for the following period.

ORDER: the number of units which a level has to order a given number of periods in advance. This order is binding; therefore the level takes a certain amount of time to react to changes in demand.

DEM: the demand for the period which is read in.

FIGURE 7: FLOW CHART FOR UNIT FLOW MODEL