"AN INDUSTRIAL DYNAMICS STUDY OF THE GROWTH OF A NEW PRODUCT"

by

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SUBMITTED IN PARTIAL FULFILLEMENT OF THE
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Signature of Author...
School of Industrial Managment

Certified by..
Faculty Advisor of Thesis

Ind. Mgmt.
Thesis
1963
M.S.

Professor Philip Franklin
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Franklin:

In accordance with the requirments for graduation I herewith submit a thesis entitled "An Industrial Dynamics Study of the Growth of a New Product."

I would like to express my appreciation to Professor Jay W. Forrestor who served as my thesis advisor for his help and guidence in bringing this thesis to a conclusion. Dr. Ross M. Cunningham, committee member, offered many helpful suggestions.

As recipient of the Albert F. Sperry Fellowship, I am indebted to the late Albert F. Sperry for his financial support. Mr. Sperry also made a generous contribution to be applied toward research in industrial dynamics.

Sincerely yours,

Hal Douglas Smith

"An Industrial Dynamics Study of the Growth of a New Product"

by

Hal Douglas Smith

"Submitted to the School of Industrial Management
on January 17, 1963, in partial fulfillment of the
requirements for the degree of Master of Science"

This thesis was a continuation of an industrial dynamics study of the growth of a new product. It extended the study to include the development of the product

The objective of the thesis was to study the sensitivity of growth to the fraction of sales budgeted to development and to test the sensitivity of the system to external disturbances. It was initially hypothesized that in the growth situation where the production capacity decision was unable to provide sufficient capacity to satisfy demand, growth would be insensitive to the fraction of sales budgeted to development and the system would be insensitive to external disturbances. In the growth situation where the production capacity decision was able to provide sufficient capacity to satisfy demand it was hypothesized that growth would be sensitive to the fraction of sales budgeted to product development and the system might amplify external disturbances and exhibit an uneven growth rate. It was also hypothesized that other situations might exist where growth would be insensitive to the fraction of sales budgeted to development.

A model was formulated to simulate the growth behavior being studied. As an initial condition the model assumed that the product had already been partially developed. The factors and events that led to the initial development of the product were not considered. Competing companies were also excluded.

The model was comprized of five sectors: the market sector, the order-filling sector, the production sector, the development sector, and the external input sector. Since the study was meant to be of general interest, the relationships considered were not limited to any particular product, but were common to a range of products.

A rigorous analysis of the computer simulations revealed that in the growth situation where the production capacity decision was unable to provide sufficient capacity to satisfy demand, growth was insensitive to the fraction of sales budgeted to development. It was also found that growth was insensitive to the fraction of sales budgeted to development in the situation where the overall time required for development was long relative to the delay between the creation of quality and the acceptance of quality by the market.

The system was insensitive to external disturbances in all growth situations studied. Initially it had been hypthesized that the system might amplify external disturbances in the growth siuation where the production capacity decision was able to provide sufficient capacity to satisfy demand.

Thesis Advisor: Jay W. Forrester

Title: Professor of Industrial Management

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CHAPTER I

INTRODUCTION

This thesis is a continuation of the study of the growth of a new product. The study was begun by Professor Jay W. Forrester in a graduate research seminar in February, 1961. The subsequent work done by Nord in his Master of Science thesis,[1] and by Nord and Swanson in a research memorandum[2] has focused on the production capacity decision. This thesis will extend the study to a system that includes the development of the product.

The study is meant to be of general interest. Accordingly, the problems considered and the model developed will not be limited to any specific product. By considering only those relationships common to a range of products, the conclusions that can be drawn from the study will be of a more general nature.

The Growth of a New Product

In considering the growth of a new product, two extreme situations may be visualized. In the one extreme, the production capacity decision is unable to provide sufficient capacity

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[1] Ole C. Nord, "The Growth of a New Product," Unpublished Master of Science thesis, M.I.T., 1962.

[2] Ole C. Nord and Carl V. Swanson, "Growth of a New Product," Unpublished Industrial Dynamics research memorandum, D-429, August 21, 1962.

to satisfy demand. Growth is characterized by a large backlog of unfilled orders and a long delivery delay. A substantial portion of the potential demand is lost because of the long delivery delay. In the other extreme, the production capacity decision is able to provide sufficient capacity to satisfy demand. Growth is characterized by a small backlog of unfilled orders and a short delivery delay. Delivery delay never becomes long enough to suppress the demand for the product.

In the following discussion the implications of these two situations are considered individually.

Insufficient Production Capacity In this growth situation we might expect growth to be relatively insensitive to the product development effort. Because the company would be unable to expand production capacity fast enough to meet demand, increasing the rate of development would have little effect upon the growth of the product. Doubling or halving the product development effort would only enlarge or attenuate the portion of the potential demand lost due to delivery delay.

The growth of the product would probably be insensitive to external disturbances. An externally induced increase in order rate would be suppressed by the reaction of the market to the longer delivery delay while an externally induced decrease in order rate would be suppressed by the reaction of the market to the shorter delivery delay. The "state of the economy," government spending, or foreign trade balances would show little tendency to induce oscillations in the growth.

Sufficient Production Capacity In this growth situation we might expect growth to be responsive to changes in product development effort. Since capacity can be expanded fast enough to meet demand, by increasing the rate of development the company could increase the growth rate of the product.

The growth of the product would probably show an increased sensitivity to external disturbances. Externally induced increases in the order rate would be amplified in the product development effort which might cause an uneven development of the product and induce fluctuations in the growth of the product.

Prior Work

Nord in his Master of Science thesis[3] and Nord and Swanson in a research memorandum[4] have made a study of the production capacity decision. They were able to show that the policy of using a linear extrapolation of order rate for forecasting future demand would tend to perpetuate a condition of

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[3] Nord, *op. cit.*
[4] Nord and Swanson, *op. cit.*

undercapacity if the delays in the system and/or the parameters of the decision allow a long delivery delay to develop. They then went on to formulate a production capacity decision that in addition to considering order rate, made an estimation of the demand lost due to the delivery delay. In comparing the behavior of the system under the policy using only order rate with the behavior of the system under the policy considering the demand lost due to delivery delay, it was found that the latter policy resulted in less undercapacity and in a more rapid growth.

They also tested the sensitivity of the system to monthly variations in the order rate. The system was found to be insensitive to this type of disturbance when the production capacity decision was unable to provide sufficient capacity to satisfy demand.

Objectives

The objective of this thesis will be to study the sensitivity of growth to product development effort and the sensitivity of the system to external disturbances. Two modes of behavior have been hypothesized:

1. In the first mode, when production capacity is insufficient to satisfy demand, the growth rate will be insensitive to the development effort and to external disturbances. Doubling or halving product

development effort will have little effect upon the growth rate; externally induced variations in the order rate will be dampened by the system.

2. In the second mode, when production capacity is sufficient to satisfy demand, the growth rate will be sensitive to the product development effort and to external disturbances. Doubling or halving product development effort will have an appreciable effect upon growth rate; externally induced variations in the order rate may be amplified by the system.

In addition, we may expect to find other situations in which growth will be insensitive to the development effort. We may also expect that the extent to which growth rate is amplified in the product development effort will affect the sensitivity of the system to external disturbances.

Scope

The study will limit itself to the problems that arise in the growth of a new product. Usually the life of a product can be divided into three stages--introduction, growth, and maturation (see Figure I-1). The factors and events that led to the initial development of the product will not be considered nor will the problems that arise with a mature product be considered. This has been done to limit the scope of the study, not because it was thought that the other stages in the life cycle of a product are unimportant.

Competition will be excluded from the study. It seems reasonable to consider first the problems that arise in a non-competitive situation before extending the study to a more complex system with competing companies. Some may prefer to think of the thesis as a study of an industry rather than a single company.

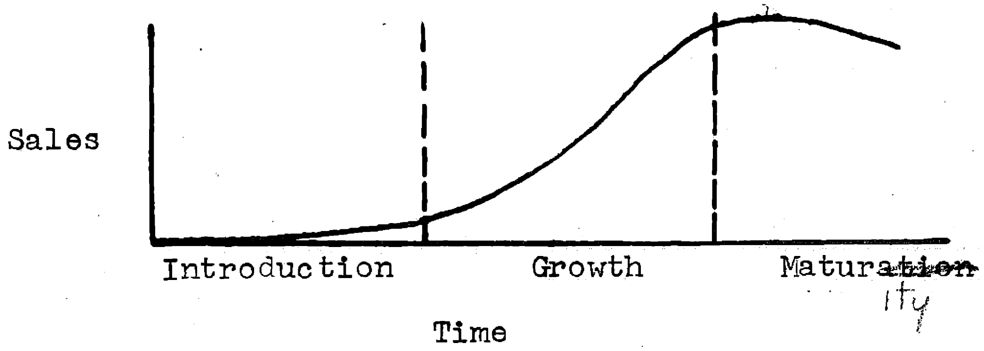

Figure I-1 The Life Cycle of a New Product.

<u>System</u>

The basic elements and feedbacks of the system are shown in Figure I-2.

The product will be characterized by quality. Product quality is here taken to be a measure of the attributes of the product that are valued by the market. In its broadest definition, product quality could be thought of as including the performance characteristics of the product as well as price.

Demand will be determined by the product quality and by the availability of the product. In general, an increase

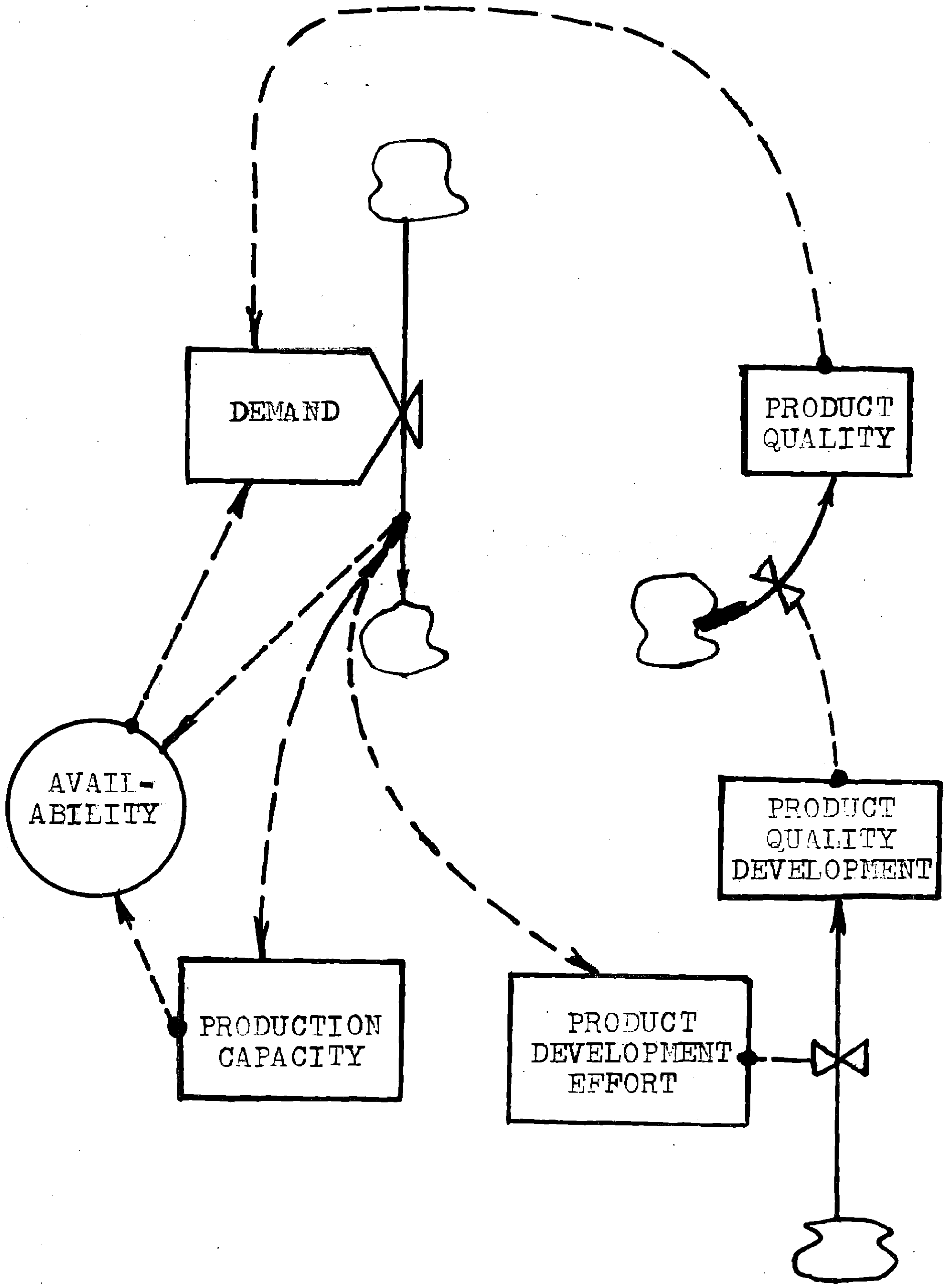

Figure I-2 The Essential Elements and Feedbacks of the System.

in product quality will increase the demand for the product. The availability of the product will affect demand to the extent that consumers become unwilling to purchase when they must wait an extended period for delivery.

The product development effort will be taken to be a fraction of the demand where demand is measured in dollars per week. Product development effort will increase the product quality at the development level. After a delay for perfecting and testing production methods, the product quality increases at the development level will be incorporated at the production level. After a delay for observing and accepting quality, the product quality at the production level will affect the demand.

Conclusion

The thesis was able to show: 1) The growth of a product will be insensitive to the fraction of sales budgeted to product development when the overall time required for development is short relative to the delay between the creation of quality and its acceptance in the market and when the production capacity decision is unable to provide sufficient capacity to satisfy demand, 2) When the market reacts to an increase in delivery delay by placing fewer orders, the growth of the product is unlikely to be sensitive to external disturbances.

Growth was insensitive to the development policy when production capacity was insufficient to satisfy demand because the more rapid development created by the more aggressive policy was offset by a higher fraction of the demand lost due to delivery delay. When the overall time for development was short relative to the delay between the creation of quality and the acceptance of quality, growth tended to be in sensitive to the development policy for two reasons: 1) Growth tended to be limited by the rate at which production methods could be developed and by the rate at which quality was accepted by the market, not by the rate at which product quality was developed, 2) The positive feedback between product development effort and order rate tended to be suppressed in this situation.

The delivery delay insulated the system from external disturbances. In the growth situation where the production capacity decision was able to provide sufficient capacity to satisfy demand, temporary overexpansions in capacity that might have made the system sensitive to external disturbances were quickly eliminated by the continuous rise in potential demand.

CHAPTER II

INDUSTRIAL DYNAMICS

This chapter is included to acquaint the reader who is unfamiliar with industrial dynamics with the approach taken in an industrial dynamics study. It is intended to be only a brief discussion of the industrial dynamics approach. For a more extensive discussion the reader is referred to Professor Jay W. Forrester's book Industrial Dynamics.[5]

Industrial dynamics was conceived by Professor Jay W. Forrester as an approach to the study of industrial and economic systems. Advances in the field of information-feedback theory, in the understanding of decision-making processes, and in the design of high speed digital computers were instrumental to its conception. The philosophy, objectives, and methodology were developed over a period of several years culminating in the recent publication of the book Industrial Dynamics.[6]

The objective of industrial dynamics is to provide a basis for analyzing and improving the stability and growth of an industrial organization. By providing a single framework for analyzing the functional areas of management--marketing, production, accounting, and research--the overall behavior of

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[5] Jay W. Forrester, Industrial Dynamics, (New York: The M.I.T. Press and John Wiley & Sons, Inc.), 1961.

[6] Ibid.

the organization can be evaluated.

It is a basic premise of industrial dynamics that industrial systems generate behavior internally that is frequently ascribed to external causes. While it may not be possible to comprehend the overall behavior of the system, it is often possible to describe the behavior of the individual parts of the system. By constructing the individual parts of the system and describing the known interaction between these parts, a system may be created that will generate internally the behavior generally ascribed to external causes. With the insight gained from observing the overall behavior of the system, the individual parts of the system can be altered to improve the behavior of the system.

The model of the system will consist of levels and flows of men, materials, money, orders, information, and capital equipment. Levels represent net accumulations. They exist as labor force, inventory, bank balance, unfilled orders, advertising awareness, and production capacity.

Flows are based upon levels and represent decisions. The production rate represents an explicit decision based on the average order rate, the inventory, and unfilled orders. The rate at which orders are processed is an implicit decision based on the number of orders being processed, a level, and the average delay for processing.

It is a cardinal principle of model building that all levels and flows have identifiable counter parts in the real system.

Parameters for the model are chosen consistent with those observed in the real system. Since some parameters may be varied by a factor of two or three without affecting the characteristic behavior of the system, estimation of a parameter by rigorous statistical analysis is avoided until model behavior has demonstrated that it is critical to the dynamic behavior of the system.

Once the model has been constructed, the behavior of the system is simulated by assuming various external inputs. The behavior of the model is compared to the observed behavior of the real system. If the model appears to be representative of the real system in all aspects to be explored, then the model builder is ready to redesign the system in order to improve its behavior.

If, however, model behavior does not coincide with the observed behavior of the real system and the model does not appear to be representative of the real system, then the model builder must go back and re-examine the model. At the very least this will necessitate the re-examination of the model parameters and in addition it may require altering the basic structure of the model.

CHAPTER III

DEFINING THE SYSTEM

The first step toward formulating a model of the system is to select the factors that interact to give the growth behavior being studied. What factors constitute the system and what factors should be considered external to the system?

The factors that will be included in the model will depend upon the questions to which the model will address itself. As the questions are altered it may be necessary to alter or extend the system.

To keep the model as simple as possible, we will include only those factors that are necessary to fulfilling the objectives of the thesis. Including factors that have little relevance to the behavior being studied will only complicate the model and obscure its behavior.

System Boundaries

If the product were to be thought of as being an industrial component, the major system sectors that could be included are shown in Figure III-1.

For an industrial component there will exist intermediate users in the form of equipment manufacturers and ultimate users in the form of equipment users. Equipment users will place orders for new equipment at the equipment manufacturers;

equipment manufacturers will place orders for components at the component supply company; and the component supply company will place orders for materials and capital equipment at the suppliers.

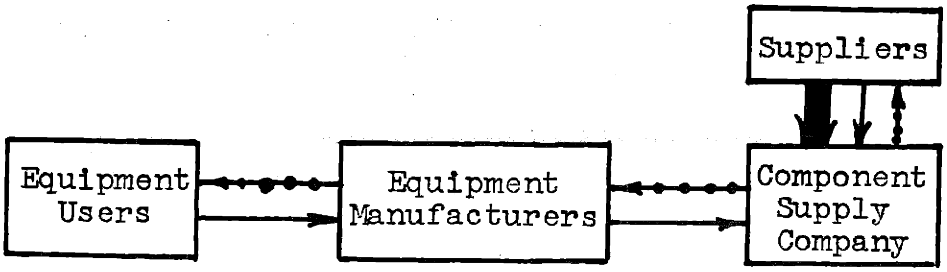

Figure III-1 Major System Sectors Considered.

We may now pose the question, what sectors must be included to study the growth behavior being considered?

Beginning with the equipment users, if the equipment users were sensitive to conditions at the component supply company, we might want to include this sector. However, it is doubtful that equipment users will be sensitive to conditions existing at the component supply company. In many cases the component may be a minor and sometimes unrecognized part of the equipment. It appears reasonable, therefore, to exclude the equipment user from the model. He will be included only to the extent that in some runs we will consider the effect of an externally induced variation in the order rate from the equipment manufacturer to the component supply company.

If the order rate from the equipment manufacturer were independent of conditions existing at the component supply company, the equipment manufacturer could be excluded. In practice, however, the order rate is usually highly sensitive to conditions existing at the component supply company. Both the product quality and the delivery delay will have a major influence on the order rate. Thus, it will be necessary to include the equipment manufacturer in the system.

The supply of raw materials for production is so seldom the cause of product shortages that it seems reasonable to exclude material suppliers as a consideration in the model. Shortages of capital equipment are the principal cause of undercapacity. However, management's inability to foresee the demand for the product and the delays in ordering and receiving the equipment are usually the cause of capital equipment shortages, not the actual supply of capital equipment. It would appear reasonable, therefore, to include the suppliers of capital equipment by a delay for receiving production capacity.

In review, we find that the objectives of the thesis can still be met with the system limited to a component supply company sector and an equipment manufacturer sector. Throughout the rest of the thesis the equipment manufacturer will be referred to as the market and the component supply company as simply the company.

Flows

Having determined the boundaries of the system, we are now in a position to determine the flows that will be considered. Again, the objective will be to include only those flows that are essential to the behavior of the system.

In general, industrial activity invlolves six interrelated flows: money, personnel, materials, capital equipment, orders, and information. These flows will be considered individually.

The supply of competent personnel for research and development may be a major consideration in the development of a large multi-system product. However, as we proceed to smaller and less complex products requiring less manpower, the supply of research personnel becomes progressively less important and the delay for reassigning personnel becomes more important. For an industrial component, it seems reasonable to represent the flow of personnel by a time delay for adjusting product development effort.

Money is more commonly a means of transaction than a determinant of behavior. The size of the backlog and the forecast of demand are likely to overshadow money considerations in the ordering of production capacity. Even if the company does not have the money required for expansion [illegible]

[illegible]

on hand, if the product show real potential, the company is unlikely to find difficulty in borrowing the necessary funds.

Likewise, the purchase decision in the market is usually motivated by the quality and availability of the product, not by money balances in the bank.

The flow of material in the form of product units will determine the availability of the product. Since the availability of the product will influence the order rate, it will be necessary to include the flow of material.

The supply of capital equipment in the form of production capacity will constrain the flow of product units into inventory. Since inventory will influence the availability of the product, it will be necessary to include the flow of capital equipment.

The flow of orders and the level of unfilled orders are important to the behavior of the system. The level of unfilled orders is particularly important since it will have a strong influence on the availability of the product which in turn will affect the order rate.

Information is the basis of the purchase decision, the production capacity decision, and the product development decision as well as other important decisions in the system. It would not be possible to study the growth problems being considered without including information flows in the system.

In review, we have excluded the flows of personnel and money from the model. We now have a system with a company sector and a market sector containing flows of materials, capital equipment, orders, and information.

System

The basic factors to be included in the system are shown in Figure II-2. The diagram will be discussed in terms of the three feedbacks.

Loop number 1 interrelates order rate, unfilled orders, and delivery delay. A rise in order rate will raise the level of unfilled orders; a rise in the level of unfilled orders will increase the delivery delay; and an increase in delivery delay will depress the order rate. This is a negative feedback loop that will tend to depress order rate whenever order rate exceeds shipments sent.

The delay around this loop will be shorter than the delay around loop 2 or loop 3. There is an implicit delay in the accumulation of unfilled orders and a delay for observing the delivery delay.

Loop number 2 interrelates order rate, unfilled orders, production capacity decision, production capacity, production rate, inventory, shipments sent, and delivery delay. The production capacity will consider order rate, unfilled orders, and inventory. After a time delay for ordering, receiving,

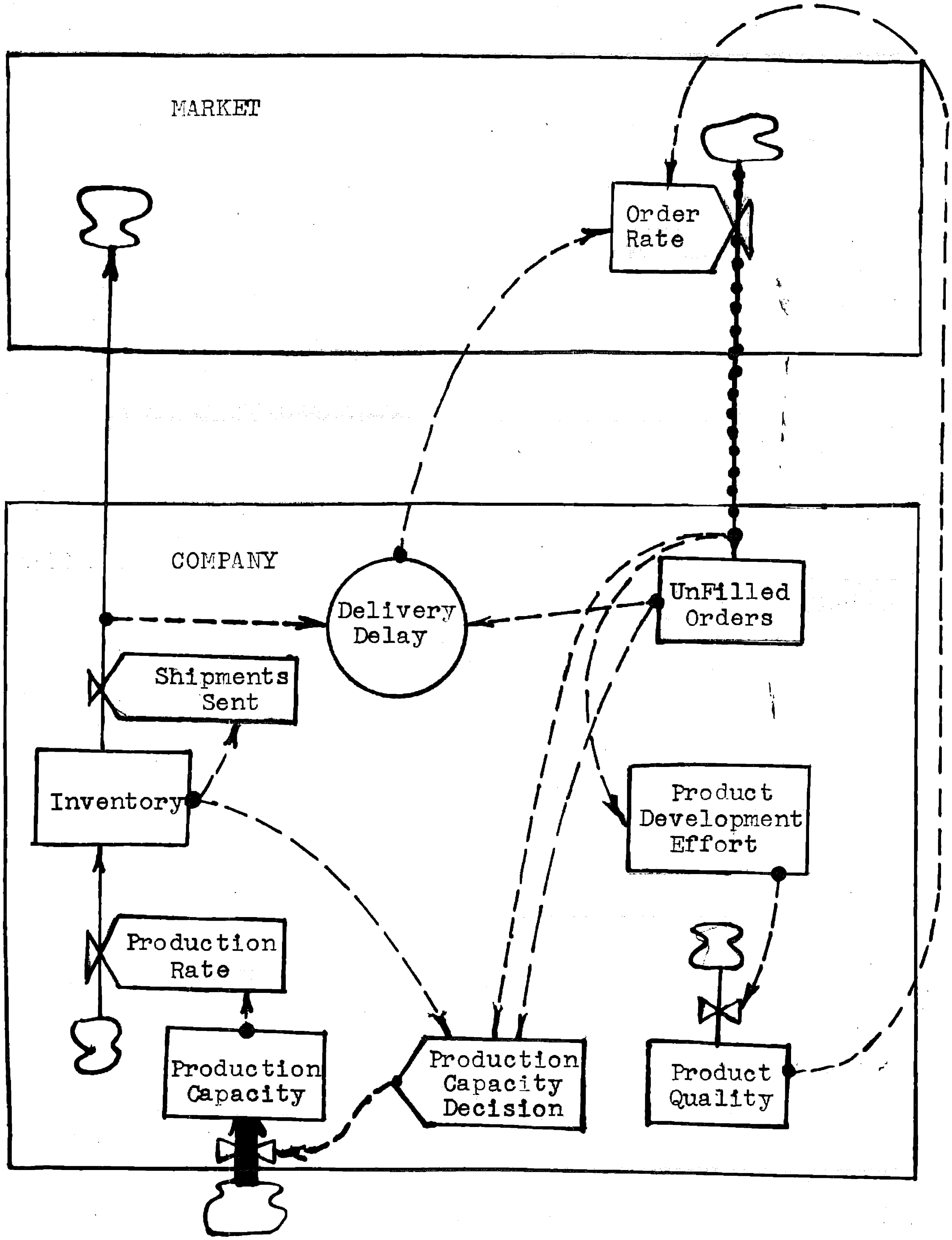

Figure III-2 The Basic Factors to be Included in the System.

and installing capacity, the production capacity decision will affect the level of production capacity. The production capacity will influence the production rate which in turn will affect the stock of inventory. The shipments sent will be responsive to inventory; delivery delay will be affected by the shipments sent; and the delivery delay will influence the order rate.

This will be a positive feedback loop that in certain growth situations will determine the growth rate. Amplification will exist in this loop from projecting order rate and from the adjustment terms for unfilled orders and inventory.

The loop will include a delay for averaging order rate, a delay for ordering production capacity, a delay for receiving and installing production capacity, and a delay for observing the delivery delay. The total delay around this loop will be longer than the delay around loop 1, but usually shorter than the delay around loop 3.

Loop number 3 interrelates order rate, product development effort, and product quality. Product development effort will be responsive to order rate; product quality will be influenced by the product development effort; and order rate will be influenced by the product quality. This is a positive feedback loop that in some growth situations will determine the growth rate.

The loop will include a delay for averaging order rate, a delay for adjusting product development effort, a delay for product development effort affecting product quality, and a delay for observing and accepting product quality. The total delay around this loop will be greater than the delay around loop 1 and usually greater than the delay around loop 2.

CHAPTER IV

MODEL DESCRIPTION AND FORMULATION

This chapter describes and formulates the model. The model is intended to be a plausible formulation of the factors that interact to create the growth behavior being studied. It is not intended to be a complete formulation of all the factors and relationships associated with the growth of a new product. The validity of the model will be judged in terms of its usefulness and its suitability to the objectives of the thesis.

The factors and relationships included in the model are common to a broad range of products. Factors or relationships that might serverely limit the generality of the model have been avoided.

The choice of parameters has been made consistent with those that could be expected for an industrial component. By altering these parameters, the model could be adapted to other types of products.

The model has been divided into five sectors: the market sector, the order-filling sector, the production sector, the development sector, and the external input sector. The market sector, order-filling sector, and production sector are based upon those developed by Nord in his Master of Science thesis[7]

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[7] Nord, op. cit.

and those used by Nord and Swanson in a research memorandum.[8] The flow diagram of the model is shown in Figure IV-1. For a print-out of the model see Appendix A.

All equations are formulated according to DYNAMO--a compiler language developed at M.I.T. specifically for simulating industrial and economic systems. An explanation of the DYNAMO equation structure is given in Appendix B.

Market Sector

This sector describes and formulates the factors that influence and give rise to an order rate. The formulation is based upon the market sector developed by Nord in his Master of Science thesis[9] and the market sector used by Nord and Swanson in a research memorandum.[10] A flow diagram of the sector is shown in Figure IV-2.

The basic assumptions of the sector are:

1. The attributes of the product that are considered important by the market can be represented by a concept of product quality.
2. The potential demand for the product is a function of the product quality.

In a recent study of the adoption of new products it was noted, "The process of adoption follows a rather uniform pattern from the time the product is developed until it is widely accepted by the ultimate consumers."[11] When the product is first introduced the rate of adoption is very

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[8] Nord, op. cit.

[9] Ibid.

[10] Nord and Swanson, op. cit.

[11] The Adoption of New Products: Process and Influence, (Ann Arbor, Michigan: Foundation for Research on Human Behavior), 1959, p. 1.

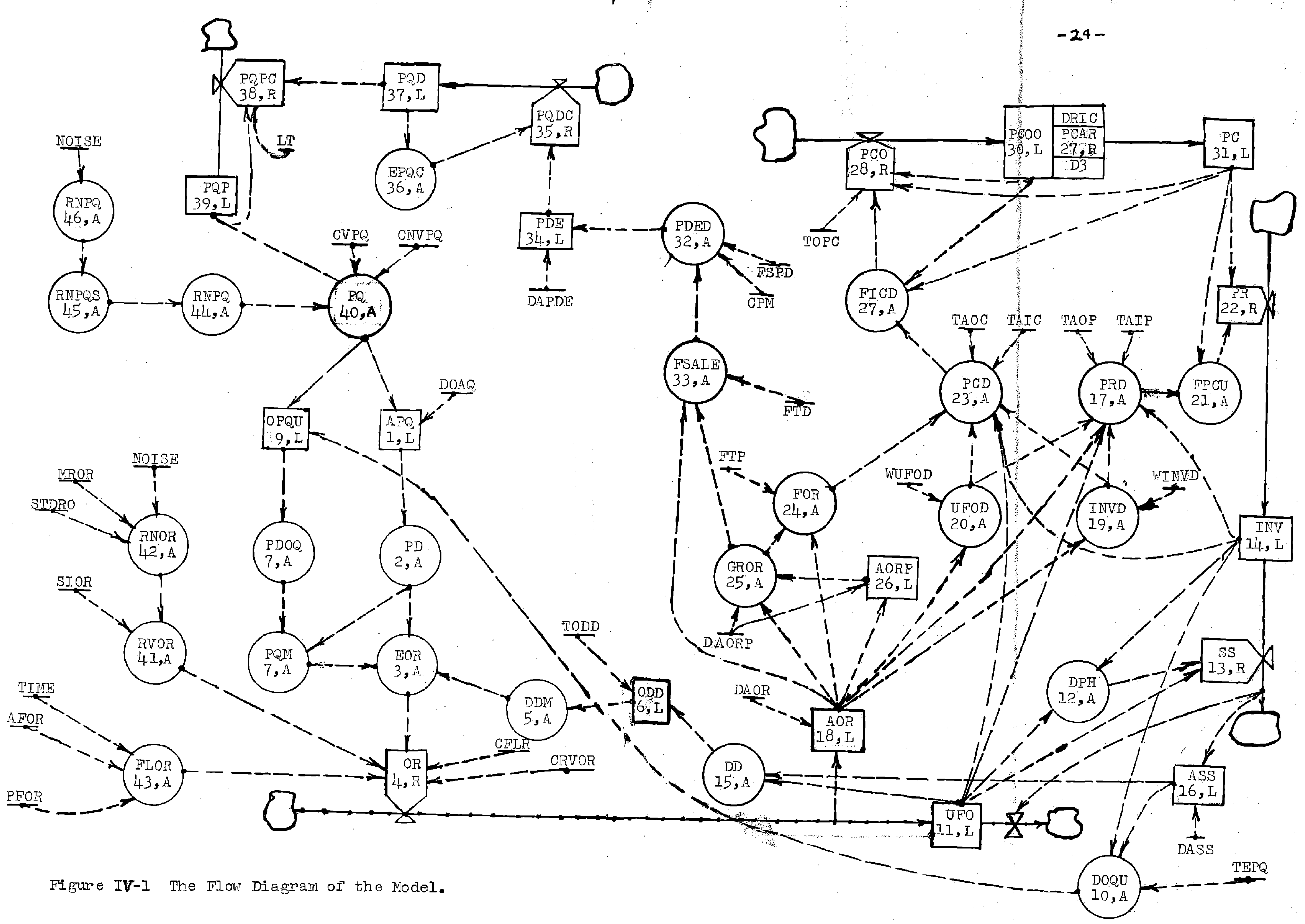

Figure IV-1 The Flow Diagram of the Model.

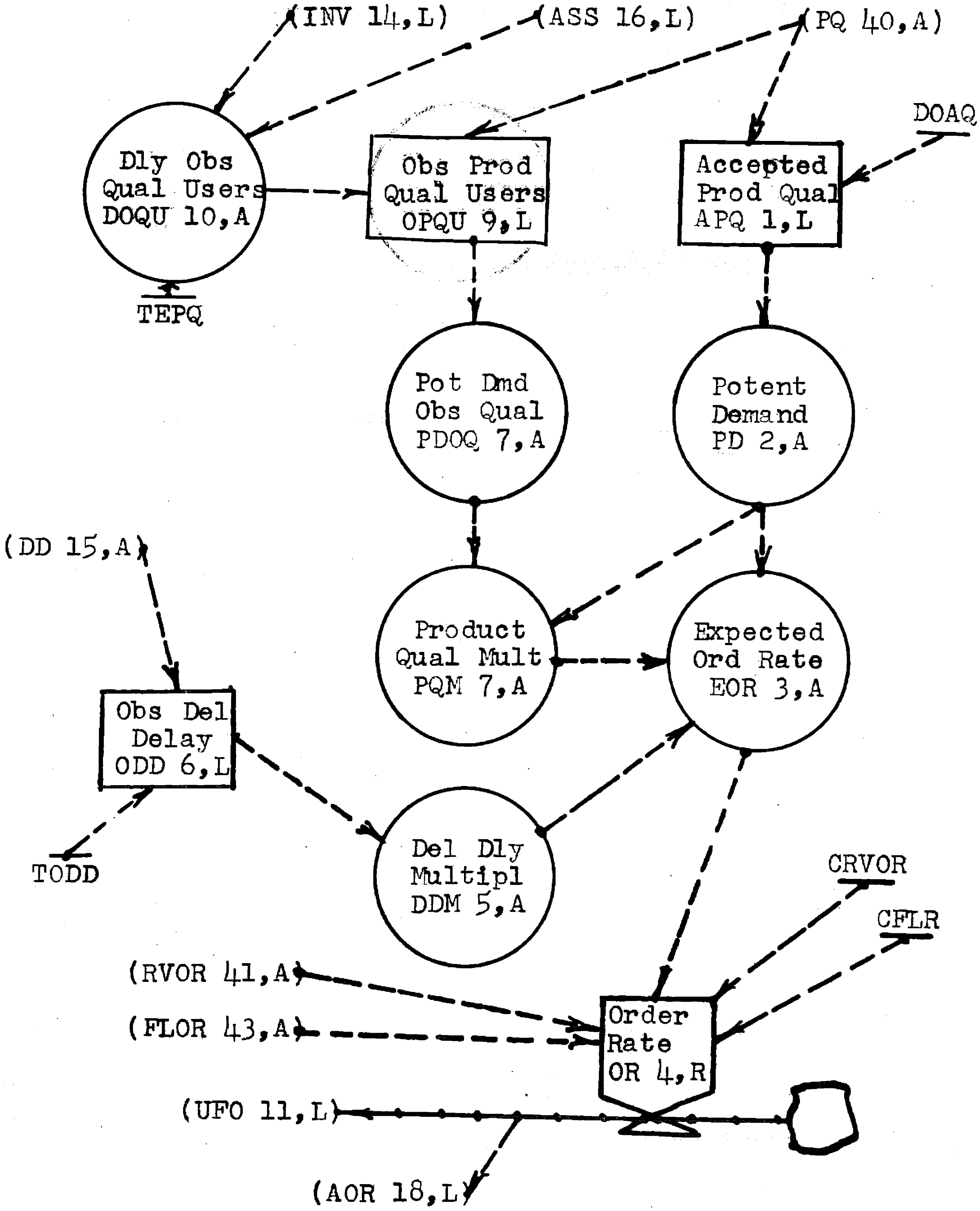

Figure IV-2 The Flow Diagram of the Market Sector.

slow. Only a few innovators sample the product. Gradually, however, the adoption rate builds up. It reaches a maximum as the product is adopted by the general market. Then the adoption rate declines as the few remaining laggards adopt the product. Researchers have charted the curve of the per cent of market adopting the product versus time and have found the shape of the curve remains constant in spite of time differences[12] (see Figure IV-3).

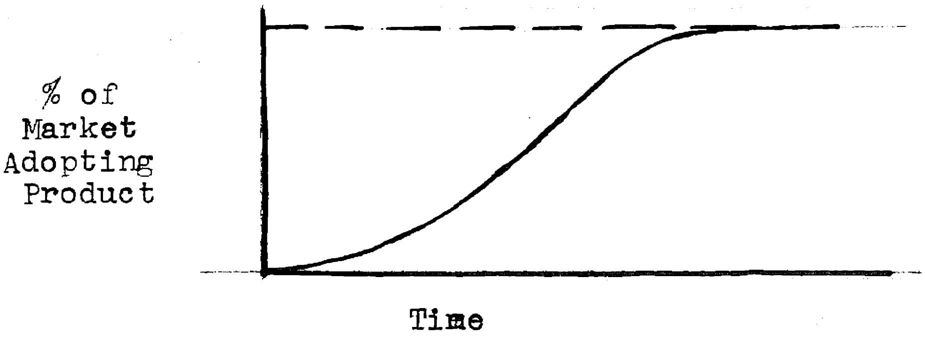

Figure IV-3 The Adoption of a New Product.

The time required for adoption will vary with the degree of change required. A product that requires a change in name only will encounter little resistance, while a product requiring the acquisition of new skills as well as adaptation of living habits may be resisted for many years.

The adoption time will also vary with the manner in which the benefits of the product accrue. If the advantages of the product can be easily demonstrated and can be realized

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[12] Ibid., p. 11.

immediately, consumers will be more disposed to accepting the product and the adoption time will be shorter. Conversely, if the advantages of the product accrue only after continued use and are not easily confirmed, consumers--unable to see an immediate payoff--will tend to procrastinate and the adoption time will be longer.

For the objectives of this thesis it does not appear to be necessary to formulate the adoption process in a rigorous manner. The adoption process will be simplified to a time delay for observing and accepting the product quality.

The accepted product quality will be formulated as a first order delay with the product quality as the input.

APQ.K = APQ.J + (DT)(1/DOAQ)(PQ.J - APQ.J) 1, L

DOAQ = 208 C

APQ - Accepted Product Quality (quality units)

PQ - Product Quality (quality units)

DOAQ - Delay for Observing and Accepting Quality (weeks)

The potential demand will be taken to be a function of the accepted product quality. The influence of price will be excluded from direct consideration. We will instead consider a product where price is not a dominating consideration in the purchase decision. In its broadest sense, product quality could be thought of as including price.

The exact relationship of potential demand to accepted product quality will vary with the particular product although it seems reasonable that the qualitative shape of the curve will remain constant. At low levels of accepted product quality we would not expect the potential demand to be very responsive to changes in product quality. The market appeal of the product would be so low that very few consumers would be interested in the product. Similarly, at high levels of accepted product quality we would not expect the potential demand to be very responsive to changes in product quality. The product would already be employed in almost every conceivable use. Increases in product quality might increase consumer satisfaction, but would do little to expand demand.

The qualitative shape of the relationship of potential demand is shown in Figure IV-4. The.numbers have been arbitrarly chosen.

PD.K= TABLE(TABPD,APQ.K,0,100,10) 2,A

TABPD*= 0/300/700/1000/2100/3800/6500/8100/9200/9700/10000 C

PD - Potential Demand (units/week)

APQ - Accepted Product Quality (quality units)

TABPD - TABle of values for Potential Demand (units/week)

TABLE - A dynamo notation for expressing the relationship between the quantity on the left and the quantity on the right by a table.

The potential demand will not always be realized in the order rate. An inability to make prompt delivery may result in loss of orders or unexpected declines in product quality may result in loss of orders.

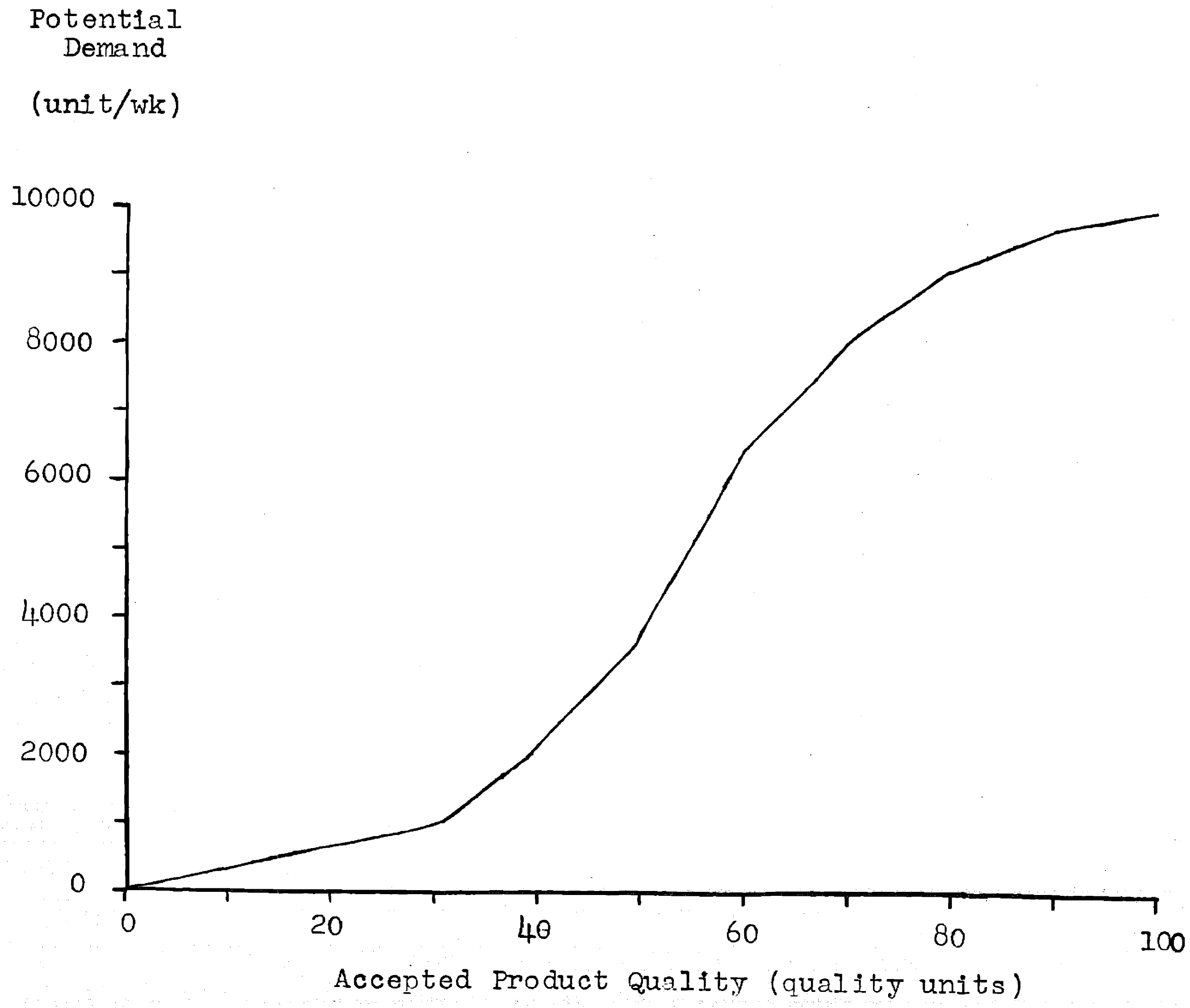

Figure IV-4 The Relationship of Potential Demand to Accepted Product Quality.

The expected order rate will be formulated as the potential demand times the product of the delivery delay multiplier and the product quality multiplier.

$$EOR.K=(PD.K)(DDM.K)(PQM.K) \qquad 3,A$$

EOR - Expected Order Rate (units/week)

PD - Potential Demand (units/week)

DDM - Delivery Delay Multiplier (dimensionless)

PQM - Product Quality Multiplier (dimensionless)

For some of the runs we will want to test the sensitivity of the system to externally induced variations in the order rate. The order rate will then be equal to the expected order rate plus the externally induced variation.

$$OR.KL=EOR.K+(EOR.K)(RVOR.K)(CRVOR)+(EOR.K)(FLOR.K)(CFLR) \qquad 4,R$$

$$CRVOR=0/CFLR=0 \qquad C$$

OR - Order Rate (units/week)

EOR - Expected Order Rate (units/week)

RVOR - Random Variations Order Rate (dimensionless)

FLOR - Fluctuations Order Rate (dimensionless)

CRVOR - Constant, Random Variations Order Rate (dimensionless)

CFLR - Constant, Fluctuations Order Rate (dimensionless)

The effect of an extended delivery delay will be to depress order rate. Potential consumers who have never used the product, and who are probably unsure of the product anyway, are likely to delay trial purchases. Users will be encouraged to seek substitutes for the product or learn to get along without it.

For an industrial component it seems reasonable that only 90% of the consumers will be willing to wait six weeks for delivery. At fifteen weeks it might be expected that only 40% of the potential demand would be realized or a twenty seven weeks only 10% of the demand would be realized.

DDM.K = TABLE(TABDD,ODD.K,0,45,3) 5,A

TABDD* = 1.0/.97/.90/.80/.62/.40/.27/.19/.14/.10/.08/
.07/.06/.05/.05/.04 C

DDM - Delivery Delay Multiplier (dimensionless)

ODD - Observed Delivery Delay (weeks)

TABDD - TABle of values for Delivery Delay multiplier (dimensionless)

In placing orders consumers will be responding to their experience with the delivery delay. Even direct inquiries to the company are not likely to yield the instantaneous value of the delivery delay. Thus, the delivery delay used in determining the delivery delay multiplier should be an observed delivery delay.

The observed delivery delay will be formulated as a first order delay.

ODD.K = ODD.J + (DT)(1/TODD)(DD.J − ODD.J) 6,L

TODD = 8 C

ODD - Observed Delivery Delay (weeks)

DD - Delivery Delay (weeks)

TODD - Time to Observe Delivery Delay (weeks)

At times unexpected declines in product quality may be observed. Particularly during periods of rising product quality and rapidly changing production methods, the product quality

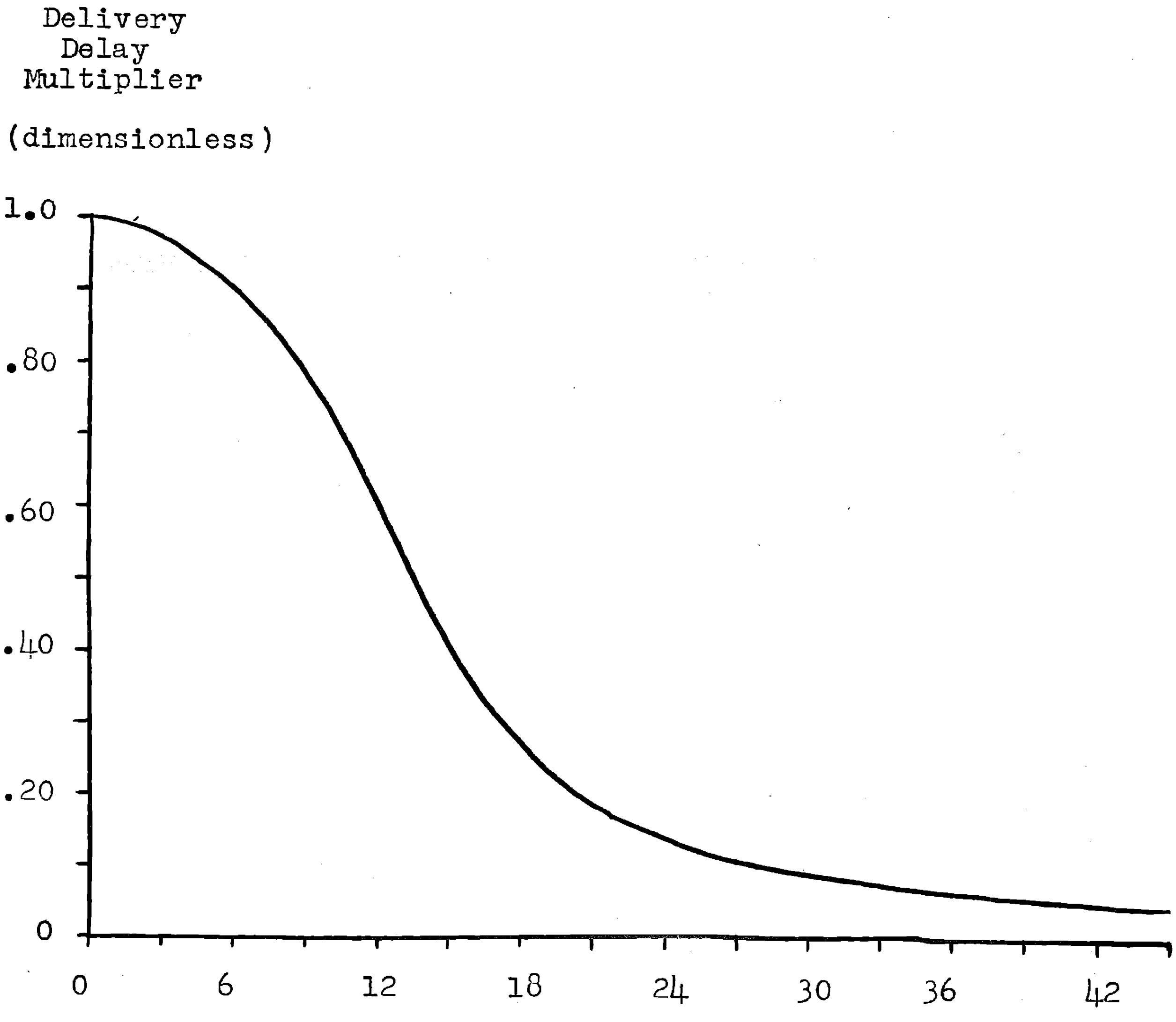

Figure IV-5 The Relationship of the Delivery Delay Multiplier to the Observed Delivery Delay.

may be susceptible to sudden and unexpected declines. Furthermore, it seems reasonable that these declines might cause some consumers to reduce purchases or to temporarily withdraw from the market.

The product quality multiplier will be formulated as a function of the ratio of the potential demand of the observed product quality users to the potential demand of the accepted product quality. (see Figure IV-6).

PQM.K = TABHL(TABQM,RDOPD.K,0,1,.5) 7,A

RDOPD.K = PDOQ.K/PD.K 7,A

TABQM* = 0/.5/1

PQM - Product Quality Multiplier (dimensionless)

RDOPD - Ratio of potential Demand Observed quality to Potential demand (dimensionless)

PDOQ - Potential Demand Observed Quality (units/week)

PD - Potential Demand (units/week)

TABQM - TABle of values for product Quality Multiplier (dimensionless)

TABHL - A dynamo notation for a table function in which all values of the quantity on the left that fall outside the table are assigned the first or last value in the table, whichever is appropriate.

The potential demand of the product quality observed by users will be a function of the observed product quality users.

PDOQ.K = TABLE(TABPD,OPQU.K,0,100,10) 8,A

PDOQ - Potential Demand of Observed Quality (units/week)

TABPD - TABle of values for Potential Demand (units/weeks)

OPQU - Observed Product Quality Users (quality units)

The table of values for potential demand is given in equation 2,A and is shown in Figure IV-4.

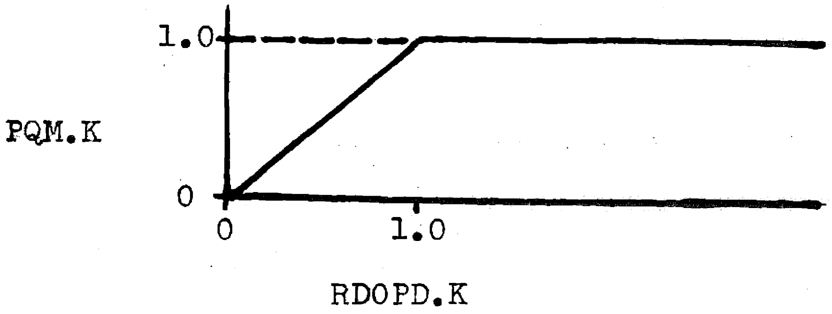

Figure IV-6 The Relationship of the Product Quality Multiplier to the Ratio of Potential Demand Observed Quality to Potential Demand.

Due to continuous contact with the product, the delay in users observing the product quality will be significantly shorter than the delay for observing and accepting product quality by the general market. The observed product quality users is formulated as a first order delay.

$$OPQU.K = OPQU.J + (DT)(1/DOQU.K)(PQ.J - OPQU.K) \qquad 9,L$$

OPQU - Observed Product Quality Users (quality units)

PQ - Product Quality (quality units)

DOQU - Delay in Observing Quality Users (weeks)

A decline in quality will not be immediately observed by users. Most defects will become apparent only after testing or prolonged usage. Even once a defect is revealed, at first it may be discounted as being an exception or the defect may be attributed to another cause. In most instances, it seems reasonable that the delay in evaluating product quality will be several weeks.

Since production units are stocked in inventory before being shipped, the delay in observing quality users will also include a delay in inventory. Assuming a first-in, first-out inventory policy, the delay in inventory will be equal to the inventory divided by the average shipments sent.

The delay in observing quality users will be formulated as the inventory delay--the inventory divided by the average shipments sent--plus the time to evaluate product quality. The time to evaluate product quality could be thought of as including a short shipping delay.

DOQU.K = INV.K/ASS.K + TEPQ 10,L

TEPQ = 26 C

DOQU - Delay in Observing Quality Users (weeks)

INV - INVentory (units)

ASS - Average Shipments Sent (units/week)

TEPQ - Time to Evaluate Product Quality (weeks)

Order-Filling Sector

This sector describes and formulates the processes involved in filling an order. The formulation is based on the order-filling sector developed by Nord in his Master of Science thesis[13] and the order-filling sector used by Nord and Swanson

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[13] Nord, *op. cit.*

in a research memorandum.[14] The flow diagram of the sector is shown in Figure IV-7.

The basic assumptions of the sector are:

1. The product is an inventorable item and all orders can be filled from inventory.
2. Orders will be shipped and processed as soon as possible.

An incoming order will be placed in a file of unfilled orders to await processing and shipping. Usually there will be a credit check made of the purchasing company. If credit is granted, the billing and shipping documents will be processed. These are sent on to the shipping department where the shipment is sent as soon as the item becomes available. At the time of shipment, the proper billing documents are sent on to the customer and the order is placed in another file.

The number of unfilled orders is the net accumulation of order rate over shipments sent. This is formulated as a simple level equation.

$$\mathrm{UFO.K} = \mathrm{UFO.J} + (\mathrm{DT})(\mathrm{OR.JK} - \mathrm{SS.JK}) \qquad 11,\mathrm{L}$$

UFO - UnFilled Orders (units)

OR - Order Rate (units/week)

SS - Shipments Sent (units/week)

It has been assumed that an order is processed and the item shipped as soon as possible. Thus, if sufficient inventory exists, we could expect the order to be filled in the minimum

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[14] Nord and Swanson, op. cit.

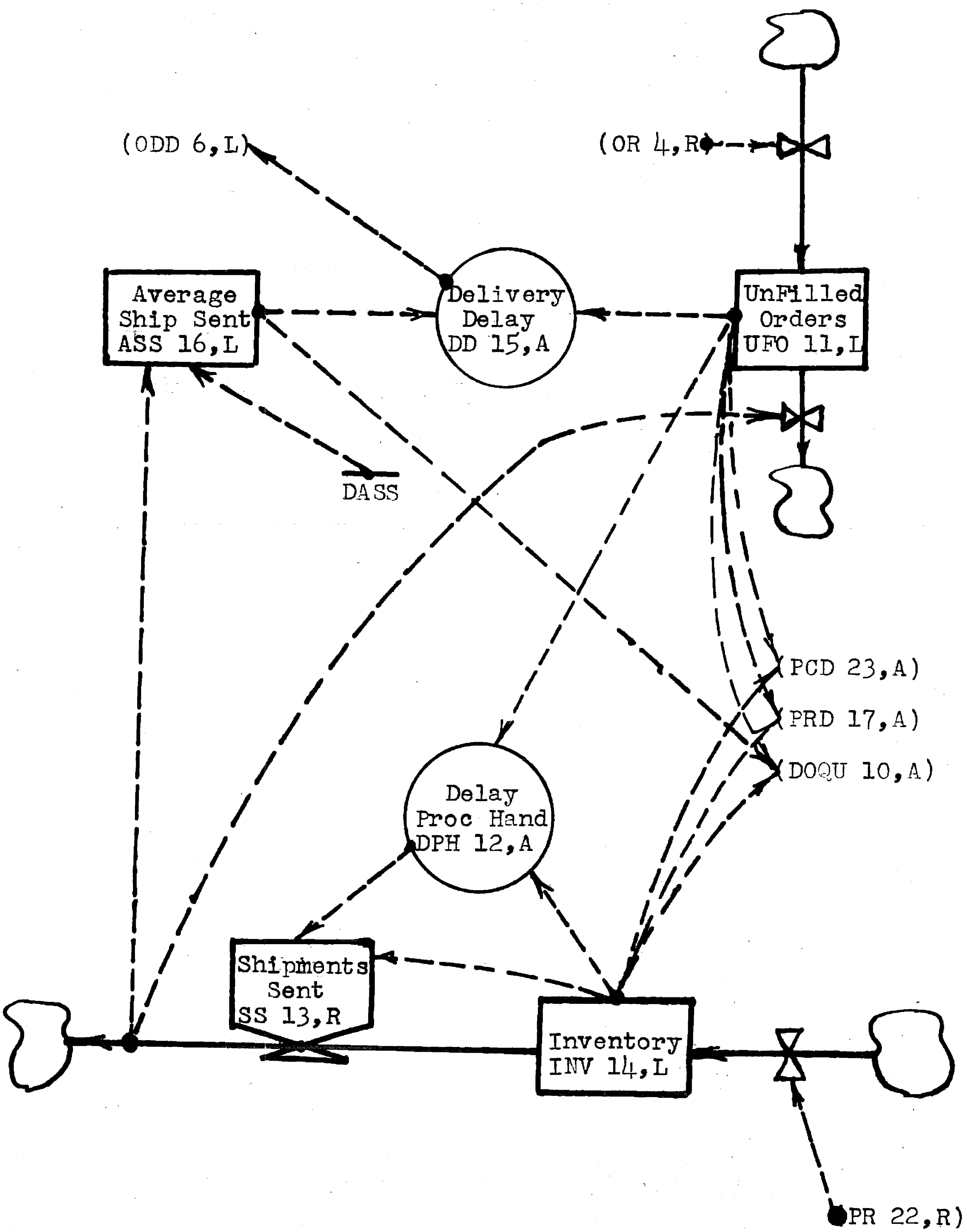

Figure IV-7 The Flow Diagram of the Order-Filling Sector.

delay required for processing of the order and the physical handling of the shipment. The rate at which shipments would be sent would be equal to the number of unfilled orders divided by the minimum delay for processing and handling.

During the growth of a new product, however, the company often finds itself in a position of undercapacity. A large backlog of unfilled orders accumulates and inventory is depleted. In this situation, the rate at which orders could be processed is constrained by the availability of inventory.

The delay for processing and handling orders will be formulated as a function of the ratio of unfilled orders to inventory. When the level of unfilled orders is low relative to inventory, the delay for processing and handling orders will be equal to the minimum delay. However, as a large backlog of unfilled orders accumulates and inventory is depleted, the delay for processing and handling will become constrained by the availability of inventory. Accordingly, the delay in processing and handling orders will rise with the ratio of unfilled orders to inventory. (see Figure IV-8).

DPH.K= TABHL(TABDP,RUOI.K,2,82,40) 12,A

RUOI.K = UFO.K/INV.K 12,A

TABDP* = 2/42/82 C

DPH - Delay in Handling and Processing (weeks)

RUOI - Ratio of Unfilled Orders to Inventory (dimensionless)

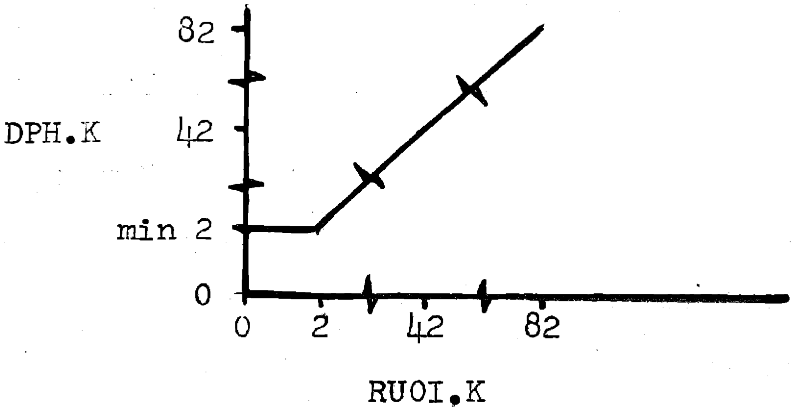

Figure IV-8 The Relationship of the Delay in Processing and Handling to the Ratio of Unfilled Orders to Inventory.

The rate at which shipments will be sent will be equal to the number of unfilled orders divided by the delay for processing and handling orders.

SS.KL = UFO.K/DPH.K 13,R

SS - Shipments Sent (units/week)

UFO - UnFilled Orders (units)

DPH - Delay in Processing and Handling (weeks)

Inventory is the net accumulation of product units produced over product units sent. Since it has been assumed that all production is taken directly into inventory, inventory will be the net accumulation of production rate over shipments sent. The inventory at time .K will be equal to the inventory at time .J plus the net accumulation of product units.

INV.K = INV.J + (DT)(PR.JK − SS.JK) 14,L

INV - INVentory (units)

PR - Production Rate (units/week)

SS - Shipments Sent (units/week)

Delivery delay represents the time between the receipt of an order and the time at which shipment is made. When inventory is at or near the desired level, the delivery delay will be equal to the minimum delay for the processing of the order and the physical handling of the shipment. At times, however, the growth of order rate will exceed the growth of production capacity. In this situation, a large backlog of unfilled orders will accumulate and inventory will be depleted. The time required for filling an order will no longer depend upon the delay for processing and handling. Instead, it will depend on how soon the item can be produced.

The delivery delay can be formulated as the number of unfilled orders divided by the average rate at which shipments are sent. When inventory is sufficient, this will give us a delivery delay equal to the minimum delay for processing and handling. When inventory is depleted, this will give us a delivery delay equal to the time required to produce a stock of product units equal to the number of unfilled orders.

DD.K=UFO.K/ASS.K 15,A

DD - Delivery Delay (weeks)

UFO - UnFilled Orders (units)

ASS - Average Shipments Sent (units/week)

An average shipments sent is necessary for the delivery delay formulation due to the day to day fluctuations that are likely to exist in the shipment rate. It is not realistic to consider a delivery delay that would fluctuate from day to day. In most situations, it seems reasonable that the delivery delay will be based on an average shipment rate.

The average shipments sent is here formulated as a first order smoothing equation.

$$ASS.K = ASS.J + (DT)(1/DASS)(SS.JK - ASS.J) \qquad 16,L$$

$$DASS = 4 \qquad C$$

ASS - Average Shipments Sent (units/week)

SS - Shipments Sent (units/week)

DASS - Delay in Averaging Shipments Sent (weeks)

Production Sector

This sector describes and formulates the factors that determine the production rate and the production capacity. The formulation of this sector is based upon the production sector developed by Nord in his Master of Science thesis[15] and the production sector used by Nord and Swanson in a research memorandum.[16] The flow diagram of the sector is shown in Figure IV-9.

The basic assumptions of the sector are:

1. In the setting of production rate and the ordering

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[15] Nord, op. cit.

[16] Nord and Swanson, op. cit.

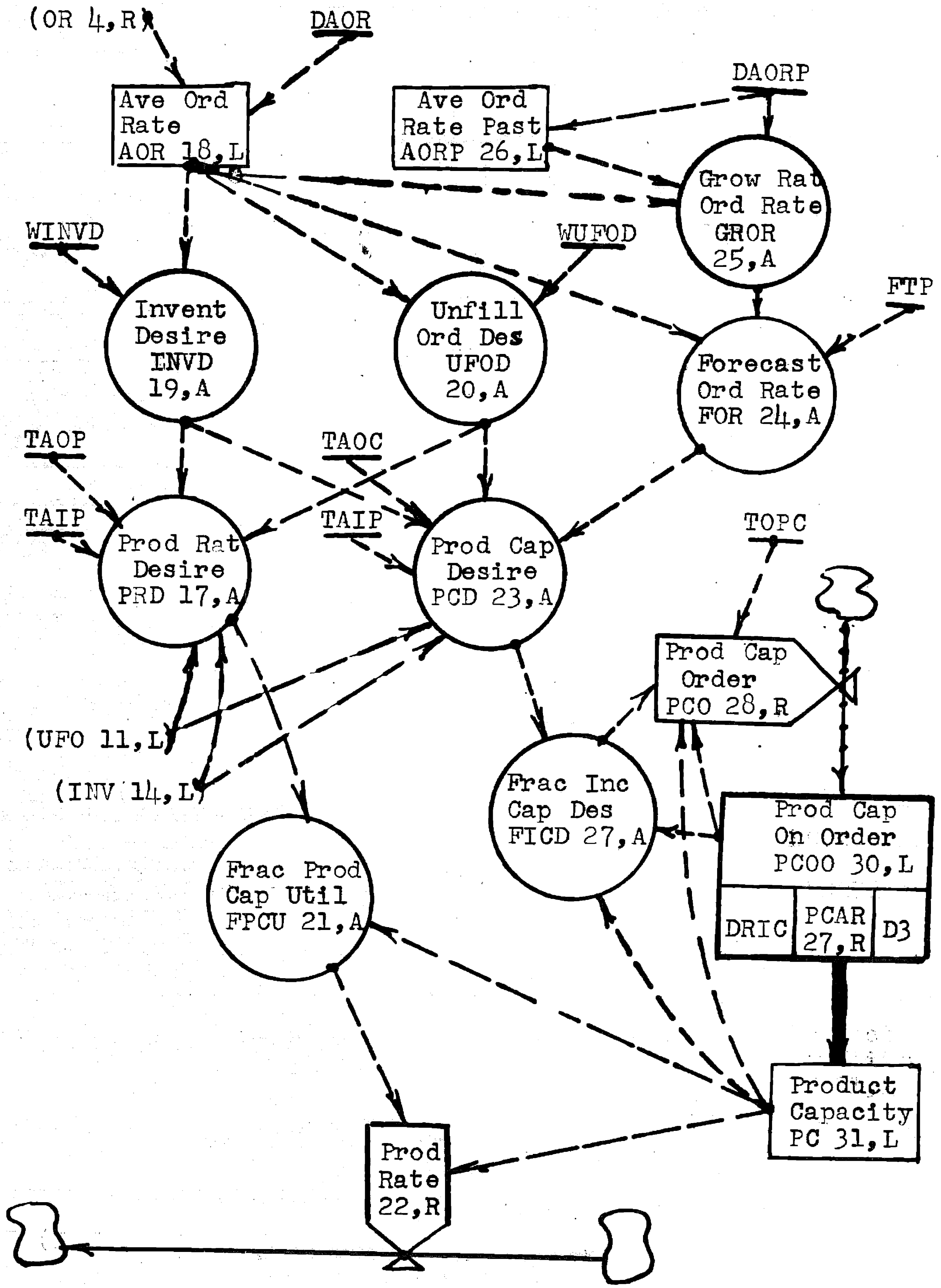

Figure IV-9 The Flow Diagram of the Production Sector.

of production capacity, the demand as well as the inventory position and unfilled order position will be considered.

2. In the ordering of production capacity the company forecasts future demand by linearly extrapolating order rate.

The production rate desired will be one that will satisfy the order rate and will make an adjustment of inventory and unfilled orders to the desired levels. Since order rate will fluctuate daily, an average order rate will be used to avoid short term fluctuations in the production rate. It also seems reasonable that inventory and unfilled orders will be adjusted to the desired levels over some adjustment period. Making an immediate adjustment to the desired levels might cause fluctuations in the production rate.

The production rate desired will be equal to the average order rate plus the difference between the desired and actual level of unfilled orders divided by the time to adjust unfilled orders plus the difference between the desired and actual level of inventory divided by the time to adjust inventory.

$$PRD.K = AOR.K + \frac{UFO.K - UFOD.K}{TAOP} + \frac{INVD.K - INV.K}{TAIP} \qquad 17,A$$

$$TAOP = 13/TAIP = 13 \qquad C$$

PRD - Production Rate Desired (units/week)

AOR - Average Order Rate (units/week)

UFOD - UnFilled Orders Desired (units)

INVD - INVentory Desired (units)

UFO - UnFilled Order (units)

INV- INVentory (units)

TAOP - Time to Adjust Orders Production (weeks)

TAIP - Time to Adjust Inventory Production (weeks)

The daily fluctuations in order rate will make it necessary to use some type of averaging technique. While averaging techniques can be used to smooth out undesirable short term fluctuations, they also introduce a certain amount of distortion in the resulting average. In particular, averaging will always tend to delay the flow of information.

Two types of averaging techniques can be identified. The moving average that gives an equal weighting to a set of time series and the exponential average that attaches a greater significance to the most recent information. Because of its simplicity and ease of computation, the moving average is frequently employed in formal averaging procedures. Exponential averaging is more frequently done unconsciously although its use in formal averaging procedures is growing.[17]

For the model, we will use an exponential averaging. At each computational interval the average order rate is adjusted by a fraction of the difference between the order rate and the average order rate.

AOR.K = AOR.J + (DT)(1/DAOR)(OR.JK - AOR.J) 18,L

DAOR = 26 C

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[17] For an analysis of exponential averaging see Forrester, op. cit., p. 408.

AOR - Average Order Rate (units/week)

OR - Order Rate (units/week)

DAOR - Delay in Averaging Order Rate (weeks)

It is a common practice in industry to adjust inventory and unfilled orders to the level of business activity. This is usually done in terms of a desired number of weeks of orders in inventory and in unfilled orders.

The inventory desired will be equal to the average order rate times the number of weeks of inventory desired.

INVD.K = (AOR.K)(WINVD) 19, A

WINVD = 8

INVD - INVentory Desired (units)

AOR - Average Order Rate (units/week)

WINVD - Weeks of INVentory Desired (weeks)

The unfilled orders desired will be equal to the average order rate times the number of weeks of unfilled orders desired.

UFOD.K = (AOR.K)(WUFOD) 20, A

WUFOD = 2 C

UFOD - UnFilled Orders Desired (units)

AOR - Average Order Rate (units/week)

WUFOD - Weeks of UnFilled Orders Desired (weeks)

The fraction of production capacity utilized will depend on the production rate desired and the production capacity. When the production rate desired is less than the production capacity, the production capacity will not be fully utilized--

the fraction of production capacity utilized will be less than one. When the production rate desired exceeds the production capacity, the production capacity will be utilized to the fullest extent--the fraction of the production capacity utilized will be equal to one.

FPCU.K = TABHL(TABCU,RPRDC.K,0,2,1) 21,A

RPRDC.K = PRD.K/PC.K 21,A

TABCU* = 0/1/1 C

FPCU - Fraction of Production Capacity Utilized (dimensionless)

RPRDC - Ratio of Production Rate Desired to Capacity (dimensionless)

PRD - Production Rate Desired (units/week)

PC - Production Capacity (units/week)

TABCU - TABle of values for Capacity Utilized (dimensionless)

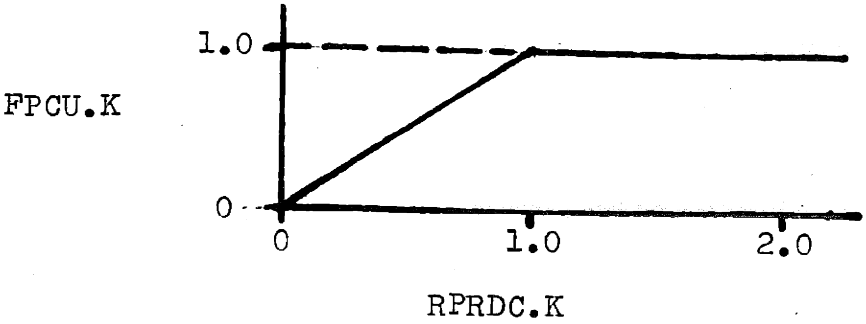


Figure IV-10 The Relationship of the Fraction of Production Capacity Utilized to the Ratio of Production Rate Desired to Production Capacity.

The production rate will be equal to the production capacity times the fraction of production capacity utilized.

PR.KL = (PC.K)(FPCU.K) 22,R

PR - Production Rate (units/week)

PC - Production Capacity (units/week)

FPCU - Fraction of Production Capacity Utilized (dimensionless)

Production capacity is here formulated as the maximum production capability. For the objectives of the thesis this seems reasonable although it should be realized that in a real situation production capacity is seldom as clearly defined. Depending on the amount of overtime or the number of shifts, a range of production rates might be termed production capacity.

While the production rate is related to the immediate production needs of the company, due to delays in receiving and installing equipment, production capacity must be ordered to meet the future production requirements. Rather than using an average order rate, we could expect the production capacity decision to be based upon a forecast of the future order rate. In addition, we could expect the production capacity decision to order capacity to make a more gradual adjustment of unfilled orders and inventory to the desired levels. The costs of disposing of excess capacity ordered to adjust inventory and unfilled orders is much greater than the costs of laying off workers hired to adjust inventories and unfilled orders.

The production capacity desired will be equal to the forecast of order rate plus the adjustment terms for unfilled orders and inventory.

$$PCD.K = FOR.K + \frac{UFO.K - UFOD.K}{TAOC} + \frac{INVD.K - INV.K}{TAIP} \qquad 23,A$$

$$TAOC = 52/TAIC = 52 \qquad C$$

PCD - Production Capacity Desired (units/week)

FOR - Forecast Order Rate (units/week)

UFOD - UnFilled Orders Desired (units)

UFO - UnFilled Orders (units)

INVD - INVentory Desired (units)

INV - INVentory (units)

TAOC - Time to Adjust unfilled Orders Capacity (weeks)

TAIC - Time to Adjust Inventory, Capacity (weeks)

While the forecasting of demand has received a great deal of attention in recent years, the practice of simply extrapolating past trends in data is still probably the most commonly employed forecasting technique. For the forecast of order rate, it seems reasonable to use a linear extrapolation of past order rate.

The forecast of order rate will be equal to the average order rate plus the growth rate of order rate times the forecast time production (see Figure IV-11).

$$FOR.K = AOR.K + (GROR.K)(FTP) \qquad 24,A$$

FOR - Forecast Order Rate (units/week)

AOR - Average Order Rate (units/week)

GROR - Growth Rate of Order Rate (units/week/week)

FTP - Forecast Time Production (weeks)

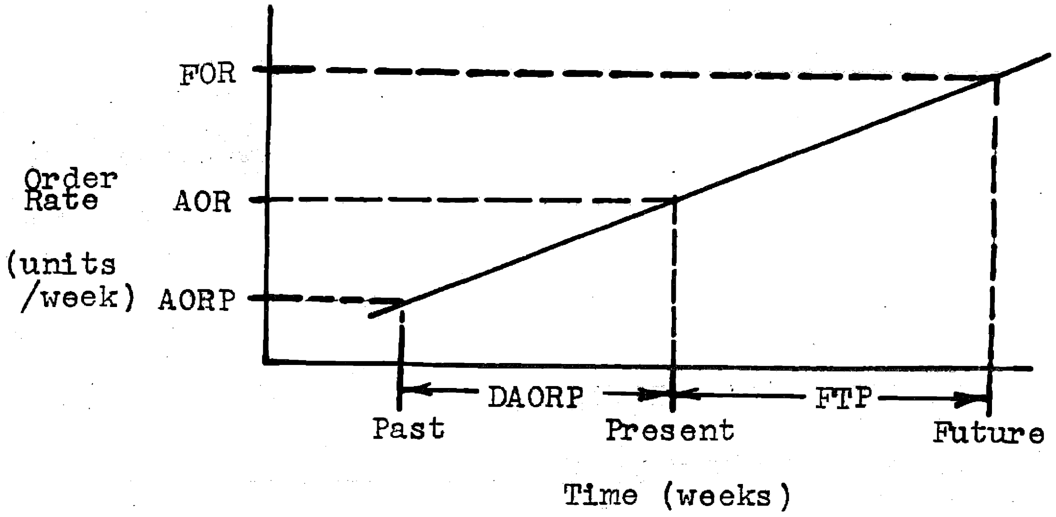


Figure IV-11 The Forecast of Order Rate.

It seems reasonable that the forecast time will be equal to the delay for receiving and installing production capacity plus the delay in averaging order rate.

FTP = DRIC + DAOR C

FTP - Forecast Time Production (weeks)

DRIC - Delay for Receiving and Installing Capacity (weeks)

DAOR - Delay for Averaging Order Rate (weeks)

The growth rate will be estimated by making comparisons of the average order rate and the average order rate in the past. The growth rate of order rate is here formulated as the difference between average order rate and the average order rate past divided by the delay in averaging order rate past.

GROR.K = (1/DAORP)(AOR.K - AORP.K) 25,A

GROR - Growth Rate of Order Rate (units/week/week)

DAORP - Delay in Averaging Order Rate Past (weeks)

AOR - Average Order Rate (units/week)

AORP - Average Order Rate Past (units/week)

The average order rate past will be equal to the average order rate delayed. A first order delay will be used.

AORP.K = AORP.J + (DT)(1/DAORP)(AOR.J - AORP.J) 26,L

DAORP = 52 C

AORP - Average Order Rate Past (units/week)

AOR - Average Order Rate (units/week)

DAORP - Delay in Averaging Order Rate Past (weeks)

The fractional increase in production capacity desired will depend on the production capacity desired, the production capacity on order, and the production capacity in operation. Additional production capacity will be wanted only when the production capacity desired exceeds the production capacity on order and in operation.

The fractional increase in production capacity desired is here formulated as a function of the ratio of the production capacity desired to the production capacity on order and in operation (see Figure IV-12).

FICD.K = TABHL(TABPC,RCDOO.K,1,21,10) 27,A

RCDOO.K = PCD.K/(PC.K + PCOO.K) 27,A

FICD - Fractional Increase in Production Capacity Desired (dimensionless)

RCDOO - Ratio of Capacity Desired to capacity on Order and in Operation (dimensionless)

PCD - Production Capacity Desired (units/week)

PC - Production Capacity (units/week)

PCOO - Production Capacity on Order and in Operation (units/week)

TABPC - TABle of values for Production Capacity (dimensionless)

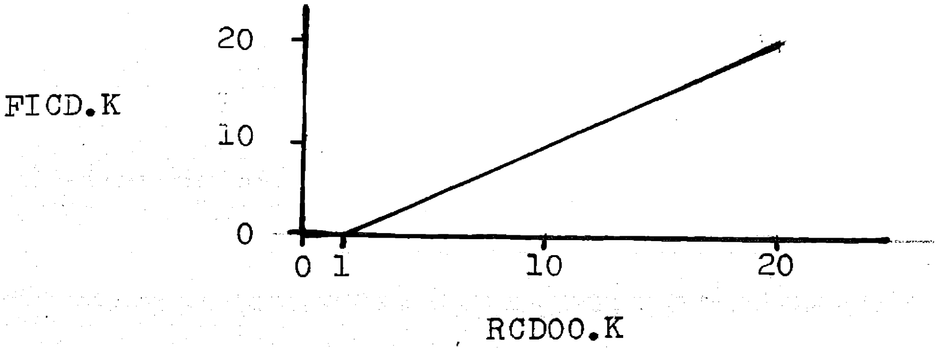


Figure IV-12 The Relationship of Fractional Increase in Capacity Desired to Ratio of Capacity Desired to Capacity on Order and in Operation.

The above formulation excludes the possibility of the company attempting to sell production capacity. For the questions to be addressed to the model this seems reasonable.

Between the initial recognition of a need for additional production capacity and the final ordering of capacity, there usually exists a sizable delay. Besides the time required for determining equipment specifications and for contacting equipment manufacturers, there is a delay for gaining acceptance of the need for additional production capacity before the necessary funds will be budgeted.

For the model these delays have been aggregated into the time to order production capacity. The production capacity ordered will be equal to the fractional increase in production capacity desired times the production capacity divided by the time for ordering prodSuction capacity.

PCO.KL = (PC.K + PCOO.K)(FICD.K)/TOPC 28,R

TOPC = 52 C

PCO - Production Capacity Ordered (units/week/week)

PC - Production Capacity (units/week)

PCOO - Production Capacity On Order (units/week)

FICD - Fractional Increase in Capacity Desired (dimensionless)

TOPC - Time to Order Production Capacity (weeks)

An order for additional production capacity may not result in an increase in production capacity for several weeks or months. Two delays can be identified as existing between the ordering of production capacity and the realization of additional production capacity.

The first of these delays is the delay for receiving production capacity. We would expect this delay to be several weeks to several months. In many cases the production equipment may be made to order. Even if the equipment is standardized, delivery conditions at the supplier may still result in a long delay in receiving production capacity.

The second delay is the time required to install and bring production capacity into operation. The equipment may require modification of existing facilities or it may require training of more workers. This delay may be several weeks.

For the model it seems reasonable to aggregate the delay delay for receiving capacity and the delay for installing capacity. The production capacity addition rate will then be formulated as a third order delay with the production capacity ordered as the input.

PCAR.KL = DELAY3(PCO.JK,DRIC) 29,R

DRIC = 52 C

PCAR - Production Capacity Addition Rate (units/week/week)

PCO - Production Capacity Ordered (units/week/week)

DRIC - Delay for Receiving and Installing Capacity (weeks)

The production capacity on order will be the net accumulation of production capacity orders over production capacity additions. This can be represented by a simple level equation.

PCOO.K = PCOO.J + (DT)(PCO.JK - PCAR.JK) 30,L

PCOO - Production Capacity On Order (units/week)

PCO - Production Capacity Ordered (units/week/week)

PCAR - Production Capacity Addition Rate (units/week/week)

The production capacity then will be a net accumulation of the production capacity additions.

PC.K = PC.J + (DT)(PCAR.JK + 0) 31,L

PC - Production Capacity (units/week)

PCAR - Production Capacity Addition Rate (units/week/week)

The simplifying assumption has been made here that no production capacity becomes obsolete. At least during the growth phase of the life cycle of a product, this assumption would not appear to unreasonable.

Development Sector

This sector describes and formulates the factors that influence and give rise to the product quality. The flow diagram of the sector is shown in Figure IV-13.

The basic assumptions of the sector are:

1. The development effort is based upon the level of sales.
2. The product has already been partially developed and has attained limited acceptance in the market.

The product quality has been defined as a composite measure of the attributes of the product considered important by the market. Depending upon the particular task to which a product will be applied, the market might consider the size, shape, durability, or other attributes of the product important. It is here assumed that the attributes of the product can be improved through product development effort.

The creation of product quality has been broken down into two steps. The first step is the working out of the idea for a design change and the development and testing of the design change on prototype models. The second step is the adaptation of production methods to incorporate the design change at the production level. We can expect the product quality at the development level to lead the product quality at the production level.

Product development effort has been taken to include all of the activity directed toward working out new ideas

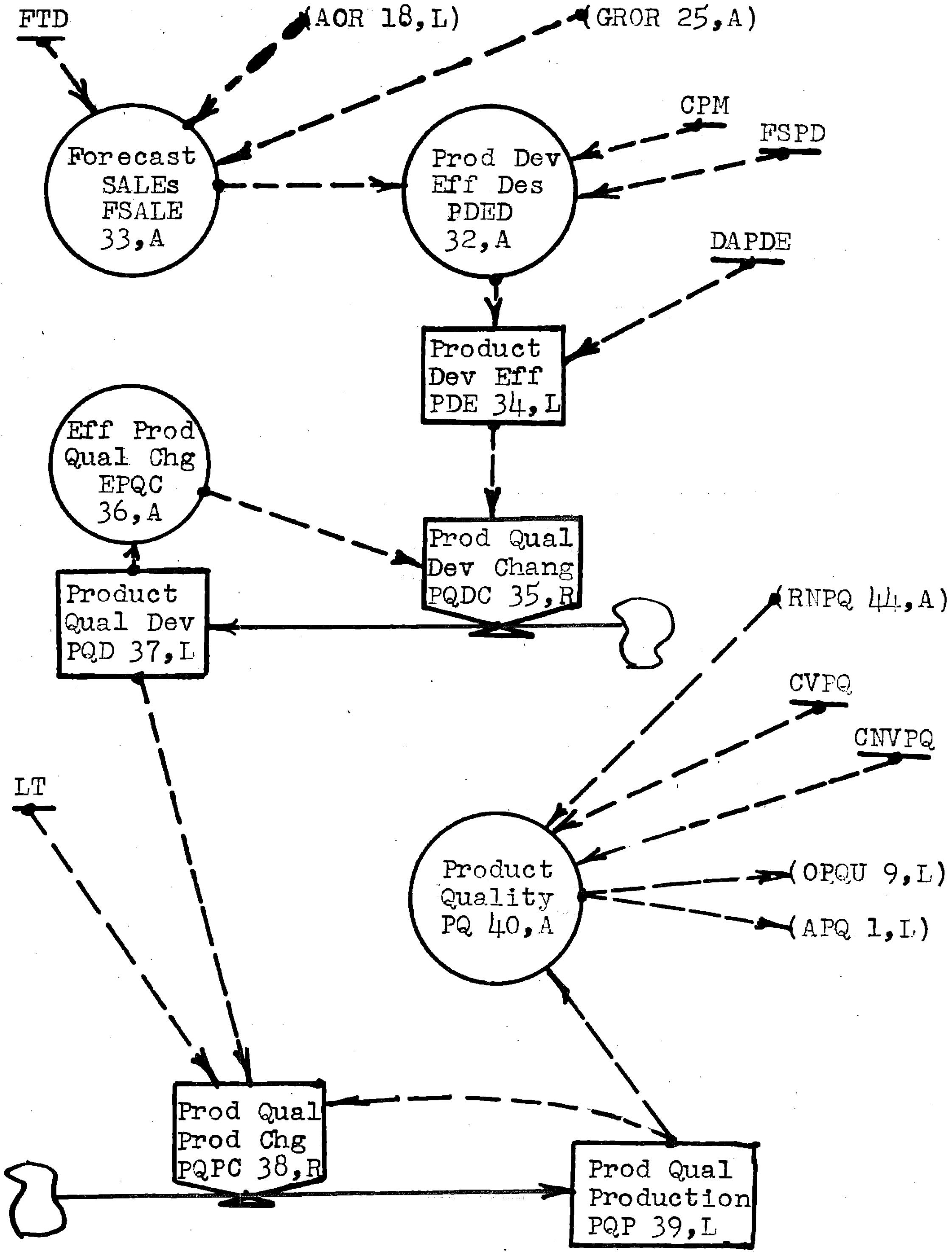


Figure IV-13 The Flow Diagram of the Development Sector.

and developing and testing them on prototype models. Research, design, and testing are all considered within the scope of product development.

A common practice among companies has been to relate product development effort to sales. Usually the product development effort is budgeted as a fraction of sales. The fraction of sales allocated to development will vary depending on the company as well as the industry. We might expect the fraction to vary from .025 to .10.

Due to the delays in adjusting product development effort, in testing and incorporating design changes, and in market acceptance of product quality increases, product development effort must be budgeted for future needs. We could expect, therefore, that the company will use a forecast of sales in budgeting product development effort.

The product development effort desired will be equal to the product of the forecast sales and the fraction of sales budgeted to product development divided by the cost per manhour.

PDED.K =(FSALE.K)(FSPD)(1/CPM) 32,A
FSPD =.05/CPM =10 C
PDED - Product Development Effort Desired (manhours/week)
FSALE - Forecast SALEs ($/week)
FSPD - Fraction of Sales budgeted to Product Development (dimensionless)
CPM - Cost Per Manhour ($/manhour)

The forecast of sales will be taken to be a linear extrapolation of order rate. We might expect that the extent to which the order rate is extrapolated into the future, the forecast time, will be critical to the behavior of the system. The longer the forecast time is, the more sensitive development will be to changes in order rate.

The forecast of sales will be equal to the price times the forecast of order rate. The forecast of order rate will be equal to the average order rate plus the growth rate of order rate times the forecast time development.

FSALE.K = (PRICE)(AOR.K + (GROR.K)(FTD))   33, A

PRICE = 10/FTD = 52   C

FSALE - Forecast SALEs ($/week)

PRICE - PRICE ($/unit)

AOR - Average Order Rate (units/week)

GROR - Growth Rate of Order Rate (units/week/week)

FTD - Forecast Time Development (weeks)

The product development effort will not be subject to immediate adjustment. Before effort can be increased, it will be necessary to determine what assignments should be extended or what new assignments should be initiated. There will also be a delay in adjusting personnel. Research personnel are likely to be fully committed to other projects and will become available only through attrition of other projects. In some cases it may even be necessary to go outside the company and hire new research personnel.

The product development effort is here formulated as a first order delay with the product development effort desired as the input.

$$\text{PDE.K} = \text{PDE.J} + (\text{DT})(1/\text{DAPDE})(\text{PDED.J} - \text{PDE.J}) \qquad 34,\text{L}$$

$$\text{DAPDE} = 52 \qquad \text{C}$$

PDE - Product Development Effort (manhours/week)

PDED - Product Development Effort Desired (manhours/week)

DAPDE - Delay in Adjusting Product Development Effort (weeks)

It will here be assumed that the product development effort will always result in an increase in product quality. Moreover, at any given stage of development, the rate of product quality change will be taken to be proportional to the product development effort. The development of product characteristics that do not inhance or that detract from the quality of the product will be considered to the extent that for some of the runs the product quality will be subject to unexpected declines.

The product quality change at the development level will be equal to the product development effort divided by the number of manhours of effort per unit of product quality change.

$$\text{PQDC.KL} = \text{PDE.K}/\text{EPQC.K} \qquad 35,\text{R}$$

PQDC - Product Quality Development Change (quality units/week)

PDE - Product Development Effort (manhours/week)

EPQC - Effort per unit of Product Quality Change (manhours/quality unit)

The effort per unit of product quality change will be taken as independent of the "state of the arts." It will be assumed that any major breakthroughs have occurred prior to the period considered in the model.

The effort per unit of product quality change will be formulated as a function of the product quality. It seems plausible that at very low levels of product quality the amount of effort required to increase the product quality will be less. Initial effort will be concentrated on developing the attributes of the product that require the least amount of effort. As the attributes most easily developed are exhausted, we would expect the amount of effort required to increase the product quality to increase. In the limit, the product could be developed to the point where no amount of effort would increase the product quality.

EPQC.K = TABLE (TABEC,PQD.K,0,100,5) 36,A

TABEC* = 200/210/220/235/250/270/290/315/340/370/400/
435/470/510/550/620/680/780/1000/10000/80000
C

EPQC - Effort per Product Quality Change (manhours/quality unit)

PQD - Product Quality Development (quality units)

TABEC - TABle of values for Effort per product quality Change (manhours/quality unit)

The product quality at the development level will be an accumulation of the product quality development change.

PQD.K = PQD.J + (DT)(PQDC.JK + 0) 37,L

PQD - Product Quality Development (quality units)

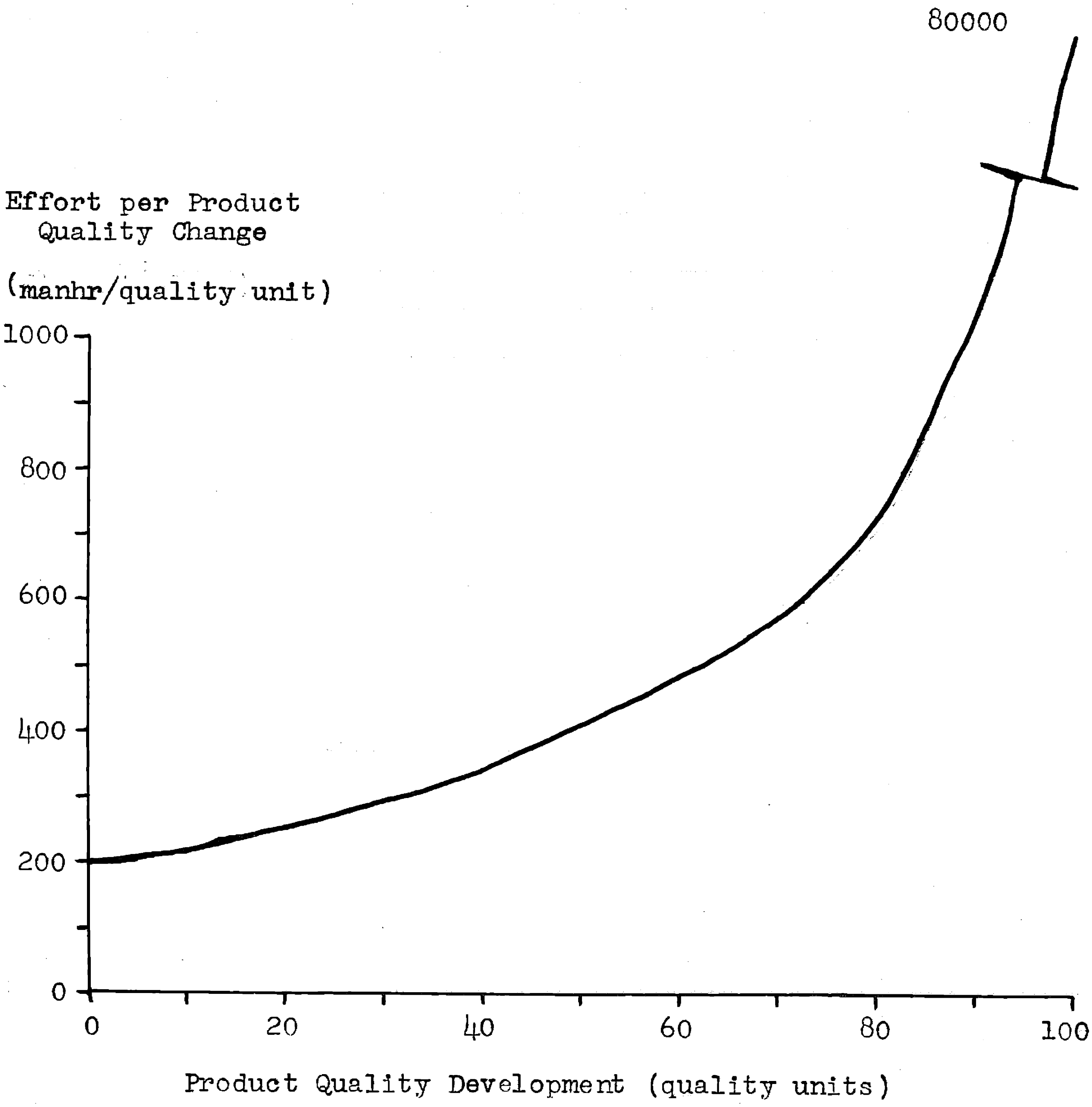


Figure IV-14 The Relationship of Effort per Product Quality Change to Product Quality Development.

PQDC - Product Quality Development Change (quality units /week)

Once a design change has been conceived and perfected at the development level, then production methods must be adapted to incorporate the design change at the production level. In some instances only minor modification of the production methods may be necessary while in other instances it may be necessary for equipment to be altered and for workers to acquire new skills. For the objectives of the study it appears reasonable to represent the adaptation of production methods to increased product quality by a time delay.

The product quality production change will be equal to the difference between the product quality development and the product quality production divided by the lead-time.

PQPC.KL = (1/LT)(PQD.K - PQP.K) 38,R

LT = 52 C

PQPC - Product Quality Production Change (quality units /week)

PQD - Product Quality Development (quality units)

PQP - Product Quality Production (quality units)

LT - Lead-Time (weeks)

The product quality production will be a net accumulation of the product quality production change.

PQP.K = PQP.J + (DT)(PQPC.JK + 0) 39,L

PQP - Product Quality Production (quality units)

PQPC - Product Quality Production Change (quality units /week)

Up to now the creation of product quality has been formulated as a smooth and continuous change. In practice, we might find changes in product quality being incorporated at regularly scheduled intervals, or we might find product quality being incorporated before the idea has been perfected or before the production methods have been perfected. In additon, raw materials, worker turnover, or equipment may cause variations in the product quality.

To test the sensitivity of the system to these types of disturbances, for some of the runs the product quality will be subject to random variations.

PQ.K = (PQP.K)(CNVPQ) + (PQP.K)(RVPQ.K)(CVPQ) 40,A

CVPQ = 0/CNVPQ = 1 C

PQ - Product Quality (quality units)

PQP - Product Quality Production (quality units)

RVPQ - Random Variations Product Quality (dimensionless)

CNVPQ - Constant No Variation Product Quality (dimensionless)

CVPQ - Constant Variation Product Quality (dimensionless)

External Input Sector

This sector describes the external inputs that will be used to test the sensitivity of the system to exogenous disturbances. The flow diagram of the sector is shown in Figure IV-15.

Up to now both the order rate and the product quality

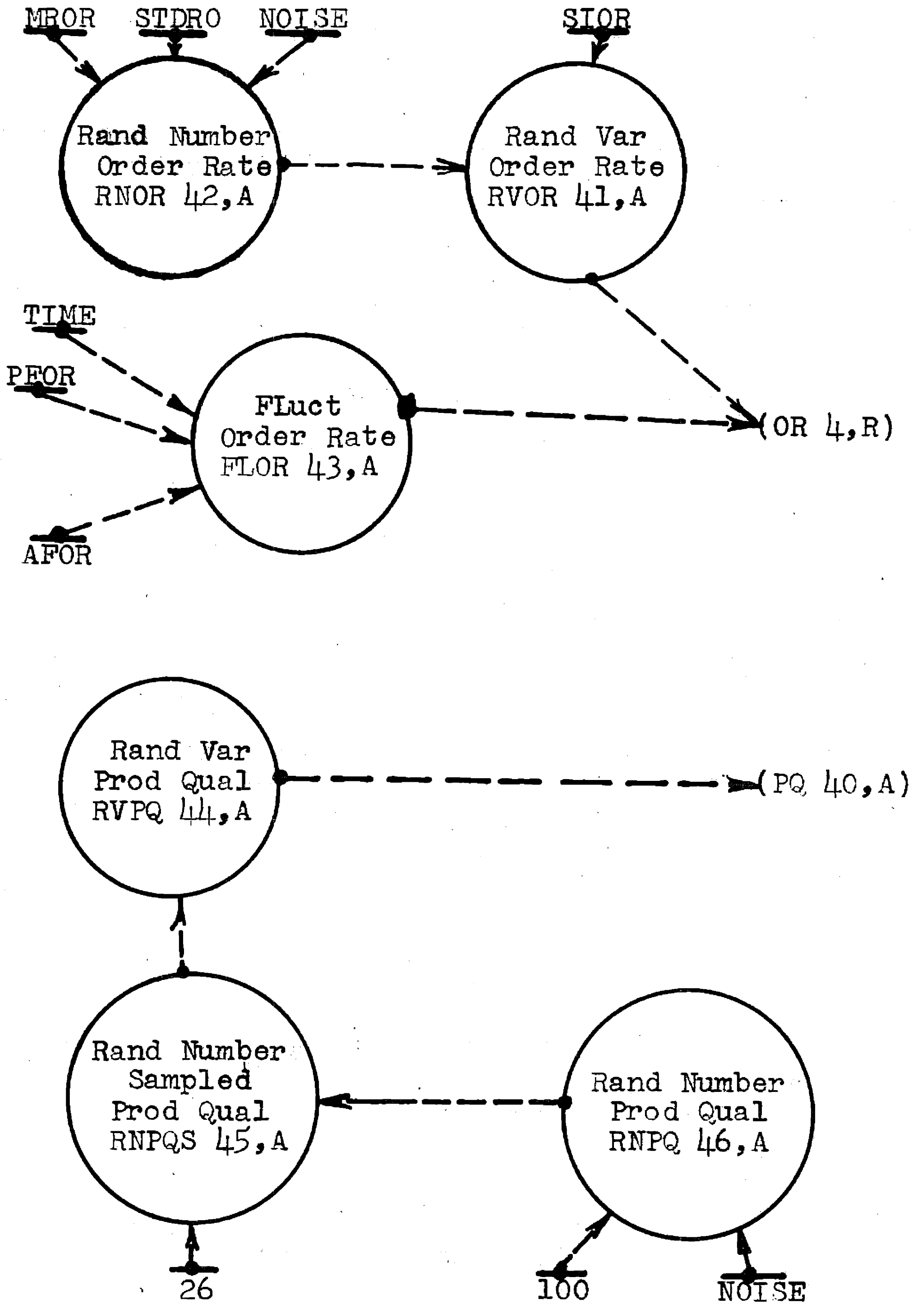


Figure IV- 15 The Flow Diagram of the External Input Sector.

have been formulated as smooth and continuous variables. In practice, however, both of these variables may exhibit noisy or fluctuating behavior. Since the thesis will concern itself with the stability of growth rate, we will want to determine under what circumstances the system is likely to amplify these disturbances and exhibit an uneven growth rate.

Random variations or periodic fluctuations could be induced in the order rate from political and economic factors that are external to the system. Several factors could be cited such as the state of the economy, government spending, foreign trade balances, or the season of the year. Two types of inputs will be considered, a noisy input and a fluctuating input.

The noisy input will be formulated as a random number normally distributed about the expected order rate. The random variation in order rate will be set equal to a random number sampled at intervals of 52 weeks.

RVOR.K = SAMPLE(RNOR.K, SIOR) 41, A

SIOR = 52 C

RVOR - Random Variation in Order Rate (dimensionless)

RNOR - Random Number Order Rate (dimensionless)

SIOR - Sampling Interval Order Rate (weeks)

SAMPLE - A dynamo notation indicating that the quantity on the left will be set equal to the quantity on the right at specified intervals.

The random number order rate will be taken from a random number generator that gives a series of random numbers normally distributed .

RNOR.K = (1)NORMRN(MROR,STDRO) 42,A

MROR = 0/STDRO = .20 C

RNOR - Random Number Order Rate (dimensionless)

MROR - Mean of Random number Order Rate (dimensionless)

STDRO - STandard Deviation of Random number Order rate (dimensionless)

NORMRN - A dynamo notation for the quantity on the left being equal to a random variable normally distributed.

The fluctuations in the order rate will be formulated as a sine wave.

FLOR.K = (AFOR)SIN((2PI)(TIME.K)/PFOR) 43,A

AFOR = .30/PFOR = 260 C

FLOR - FLuctuations Order Rate (dimensionless)

AFOR - Amplitude of Fluctuations Order Rate (dimensionless)

PFOR - Period of Fluctuations Order Rate (weeks)

TIME - TIME (weeks)

SIN - A dynamo notation for the quantity on the left being a sine wave of the period and amplitude specified.

In the development sector product quality was assumed to always rise with development effort. However, in practice during periods of rapidly changing product quality where changes in design and specifications occur frequently, the company may experience problems in adapting production methods or it may incorporate design changes before the change has been properly tested. The result in either case could be a temporary decline in product quality.

The random variation in product quality will be taken as a function of a random number sampled at intervals of 26 weeks. The relationship between the random variation product quality and the random number product quality will be taken as exponential (see Figure IV-16). Thus, the probability of a given decline in product quality will decrease with the extent of the decline.

RVPQ.K = TABLE(TABVQ,RNPQS.K,-50,50,10) 44,A

TABVQ* = 1.0/1.0/.99/.97/.96/.94/.91/.86/.75/.40 C

RVPQ - Random Variation Product Quality (dimensionless)

RNPQS - Random Number Product Quality Sampled (dimensionless)

TABVQ - TABle of values for Variations Quality (dimensionless)

The random number product quality will be sampled at intervals of 26 weeks.

RNPQS.K = SAMPLE(RNPQ.K,26) 45,A

RNPQ.K = (100)NOISE 46,A

RNPQS - Random Number Product Quality Sampled (dimensionless)

RNPQ - Random Number Product Quality (dimensionless)

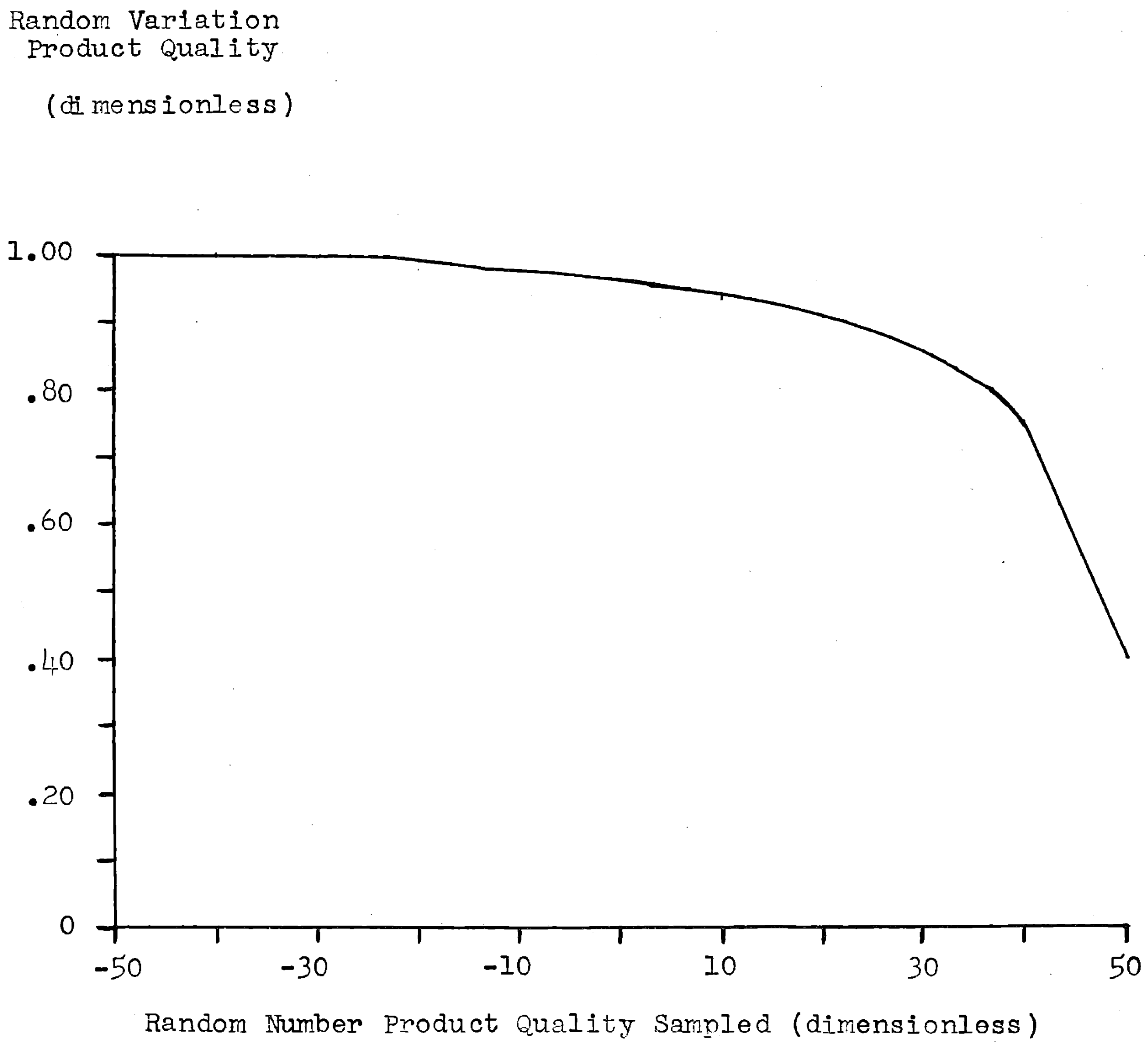


Figure IV-16 The Relationship of Random Variation Product Quality to Random Number Product Quality Sampled.

CHAPTER V

ANALYSIS OF THE MODEL

The analysis of the model has been broken down into two sections. In the first section the three principal feedback loops that control the behavior of the system will be examined in greater detail. The second section describes and analyzes the computer runs.

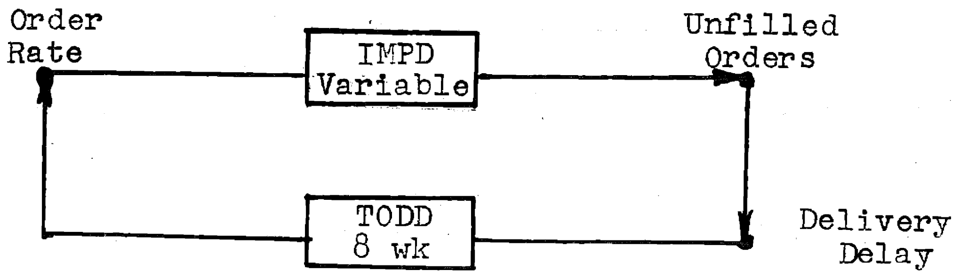
I. Analysis of the Feedbacks

In chapter III the system was described in terms of three feedback loops (see Figure III-2). For formulating and analyzing the computer runs, it will be helpful to re-examine the delays and sources of amplification in these feedback loops in greater detail. In the following discussion each of these feedback loops will be considered individually.

Loop Number 1

Loop number 1 is a negative feedback loop that interrelates order rate, unfilled orders, and delivery delay (see Figure V-1). When order rate rises above the production capacity, unfilled orders will accumulate and the delivery delay will lengthen until the delivery delay becomes long enough to suppress the initial rise in order rate. Whenever demand exceeds production capacity, this feedback will depress order rate to the production capacity.

Two delays exist in this feedback loop. The most obvious of these is the delay for observing the delivery delay. In addition, there exists an implicit delay in the level of unfilled orders. A rise in order rate will continue to raise the level of unfilled orders until the delivery delay has been increased to the point where it depresses order rate to the production capacity level.[17] The total delay around this loop will be shorter than the delay around loop 2 or loop 3.



IMPD - IMPlicit Delay (weeks)

TODD - Time to Observe Delivery Delay (weeks)

Figure V-1 Feedback Loop Number 1.

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[17] The length of this delay will vary with the relationship between the delivery delay multiplier and the observed delivery delay. If a two week increase in the delivery delay would cause a 5% decline in order rate, the implicit delay in loop 1 would be 40 weeks.

$$\text{Implicit Delay} = \frac{\text{Delivery Delay Increase}}{\text{\% Decrease Order Rate for Delivery Delay Increase}} = \frac{2}{.05} = 40 \text{ weeks}$$

Loop Number 2

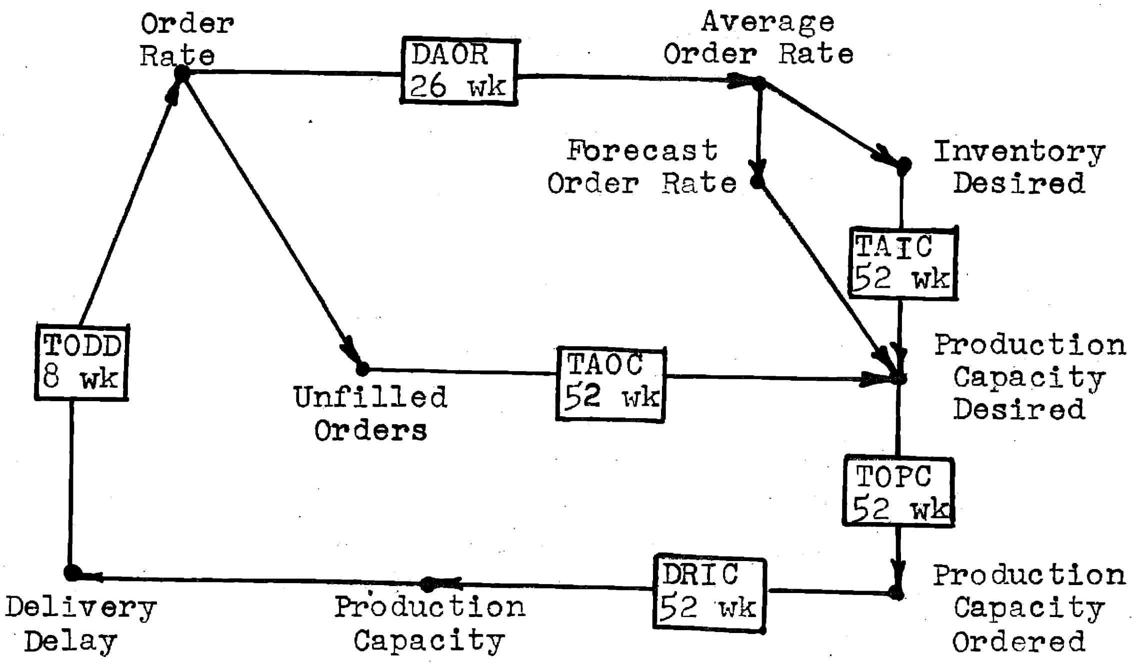
Loop number 2 is a positive feedback loop that interrelates order rate, average order rate, forecast order rate, inventory desired, unfilled orders, production capacity desired, production capacity ordered, production capacity, and delivery delay (see Figure V-2). When the delays and amplification around this loop produce a slower buildup of production capacity than the buildup of demand created by loop 3, order rate will be determined by the production capacity and the growth rate will be limited by this loop.

This loop contains six delays: the delay for averaging order rate, the delay for adjusting inventory, the delay for adjusting unfilled orders, the delay for ordering production capacity, the delay for receiving and installing capacity, and the delay for observing delivery delay. The total delay around this loop will be longer than the delay around loop 1, but normally shorter than the delay around loop 3.

Amplification exists in this loop from extrapolating the growth of order rate and from adjusting inventory to a level proportional to the order rate. Increasing the forecast time or increasing the the weeks of inventory desired will increase the amplification in this loop.

Loop Number 3

Loop number 3 is a positive feedback loop that interrelates order rate, product development effort desired, product



DAOR - Delay in Averaging Order Rate (weeks)

TAOC - Time to Adjust Orders Capacity (weeks)

TAIC - Time to Adjust Inventory Capacity (weeks)

TOPC - Time to Order Production Capacity (weeks)

DRIC - Delay in Receiving and Installing Capacity (weeks)

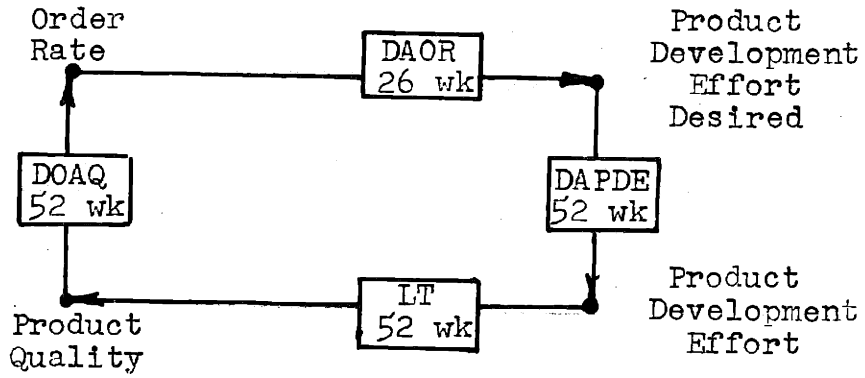
TODD - Time to Observe Delivery Delay (weeks)

Figure V-2 Feedback Loop Number 2.

development effort, and product quality. When the delays and amplification around this loop create a buildup of demand slower than the rate at which production capacity can be expanded, order rate will be determined by the product quality and the growth rate will be limited by this loop.

This loop contains four delays: the delay in averaging order rate, the delay in adjusting product development effort, the lead-time for incorporating design changes at the production level, and the delay for observing and accepting product quality. Normally the delay around this loop is longer than the delay around either loop 2 or loop 3.

Amplification exists in this loop from forecasting the order rate. Increasing the forecast time will increase the amplification in this loop.



DAOR - Delay for Averaging Order Rate (weeks)

DAPDE - Delay for Adjusting Product Development Effort (weeks)

LT - Lead-Time (weeks)

DOAQ - Delay for Observing and Accepting Quality (weeks)

Figure V-3 Feedback Loop Number 3.

II. Analysis of the Computer Runs

The objective of this thesis was to test the sensitivity of the system to the product development policy and to low frequency disturbances. Initially it was hypothesized that in the growth situation where the production capacity decision was unable to provide sufficient capacity to satisfy demand, the system would be insensitive to both the development policy and to externally induced disturbances. In the growth situation where the production capacity decision was able to provide sufficient capacity to satisfy demand, it was hypothesized that the system would be responsive to the development policy and the externally induced disturbances might be amplified by the system.

These two growth situations were created in the model by altering the delay for receiving and installing capacity, the time to adjust unfilled orders, the time to order production capacity, and the delay in observing and accepting quality. The choice of parameters is given below.

1. Insufficient Production Capacity
   DRIC = 104
   TAOC = 52
   TOPC = 52
   DOAQ = 104
2. Sufficient Production Capacity
   DRIC = 26
   TAOC = 26
   TOPC = 26
   DOAQ = 208

DRIC - Delay in Receiving and Installing Capacity (weeks)
TAOC - Time to Adjust unfilled Orders Capacity (weeks)
TOPC - Time to Order Production Capacity (weeks)

The analysis of the computer runs is broken down into two sections. The first section describes and analyzes the computer runs made to test the sensitivity of the model to the development policy. The second section describes and analyzes the runs made to test the sensitivity of the model to low frequency disturbances.

Sensitivity to Development Policy

Four sets of runs were made to study the sensitivity of the model to the product development policy (see Figure V-4). The first and second set of runs were formulated to determine the sensitivity of the model to the development policy in the two hypothesized growth situations. The third set of runs was formulated to determine how the delay around loop 3 may affect the sensitivity of the model to the development policy while the fourth set of runs was formulated to determine the effect of increasing the amplification in the product development policy.

For discussion purposes the three development policies of budgeting development effort as .025, .05, and .10 of sales will be distinguished as the passive policy, the average policy, and the aggressive policy.

SET	RUN	FSPD	DOAQ	DRIC	TAOC	TOPC	FTD	DELAY AROUND LOOP 3
1 -- To Determine Sensitivity for Insufficient Capacity								
	1	.025	104	104	52	52	52	234
	2	.050	"	"	"	"	"	"
	3	.100	"	"	"	"	"	"
2 -- To Determine Sensitivity for Sufficient Capacity								
	4	.025	208	26	26	26	52	338
	5	.050	"	"	"	"	"	"
	6	.100	"	"	"	"	"	"
3 -- To Determine Sensitivity for Short and Long Delay in Loop 3								
	7	.100	208	26	26	26	52	338
	8	.025	"		"	"	"	"
	9	.100	52	"	"	"	26	130
	10	.025	"	"	"	"	"	"
	11	.025	208	"	"	"	52	338
	12	.050	"	"	"	"	"	"
	13	.100	"	"	"	"	"	"
4 -- To Determine Sensitivity to Amplification in Product Development Effort								
	14	.050	208	26	26	26	52	338
	15	"	"	"	"	"	104	"
	16	"	52	"	"	"	26	130
	17	"	"	"	"	"	52	"

Figure V-4 Computer Runs to Test the Sensitivity of the Model to the Development Policy.

FSPD - Fraction of Sales Budgeted to Product Development (dimensionless)

DOAQ - Delay in Observing and Accepting Quality (weeks)

DRIC - Delay in Receiving and Installing Capacity (weeks)

TAOC - Time to Adjust unfilled Orders Capacity (weeks)

FTD - Forecast Time Development (weeks)

TOPC - Time to Order Production Capacity (weeks)

<u>Insufficient Production Capacity</u> In the first three runs all model parameters were held constant except for the development policy. All three runs were characterized by a long delivery delay and a latent demand for the product. Since the behavior of the model was qualitatively the same in all three runs, only run 2 will be discussed in detail. Runs 1 and 3 will then be compared to run 2.

Run number 2 using the average development policy is shown in Figure V-5. Throughout most of the run production capacity is insufficient to satisfy the demand for the product. From week 247 to week 650 (a period of almost 8 years) 50% of the demand is lost because of the long delivery delay. In consequence, although the potential demand for the product begins to saturate at week 650, it is not until week 910 or 5 years later that the order rate saturates. A total of 4,252,000 orders were received during the run.

It may be noted that although production capacity is insufficient to satisfy demand throughout the growth period, at the end of growth the company finds itself burdened with

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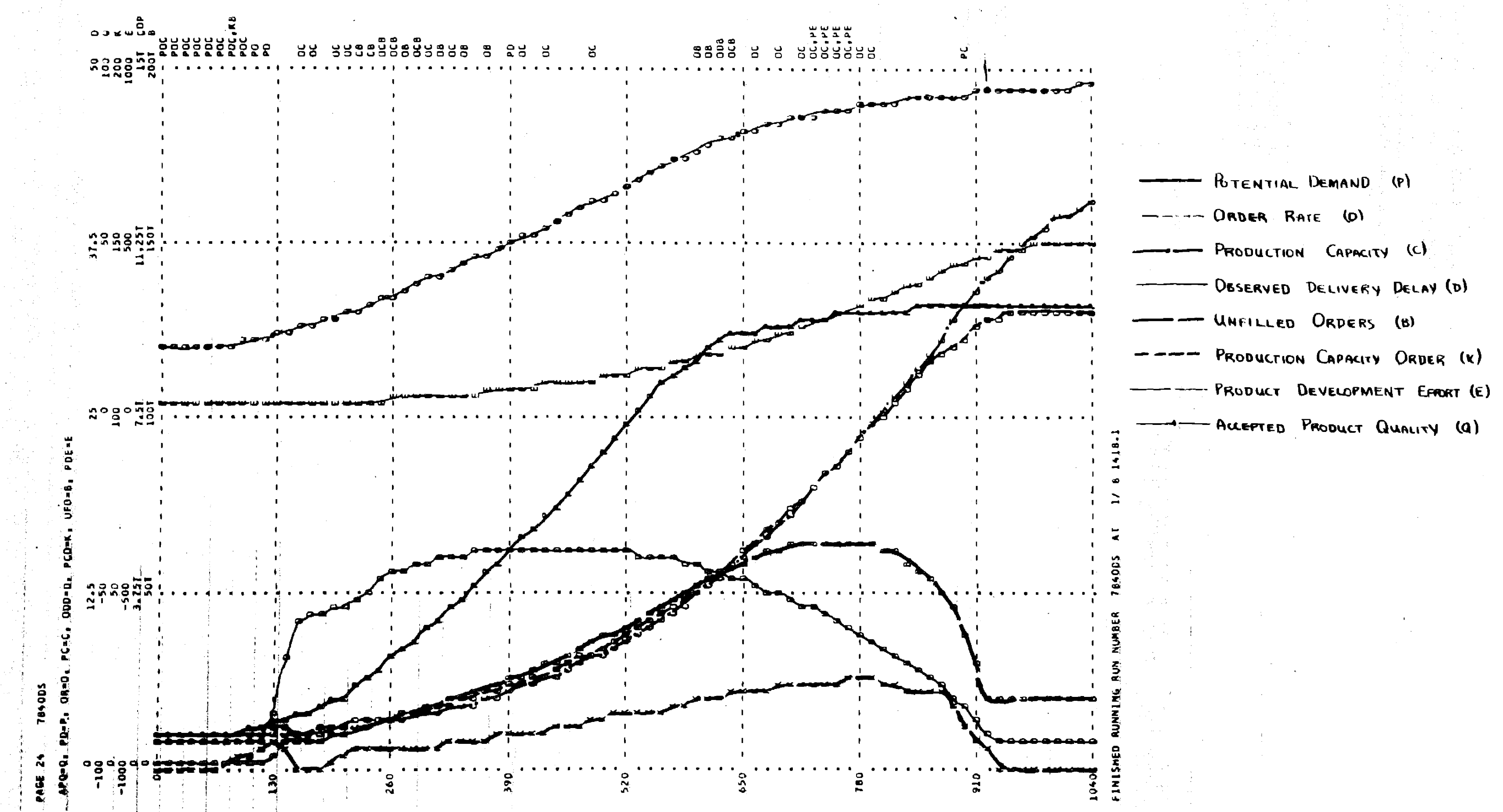

Figure V-5 Run Number 2

with 27% excess capacity. The excess capacity arises from projecting the growth of order rate beyond the saturation level and from ordering capacity to adjust unfilled orders and inventory.

The product development effort (PDE) is initially 35 hours per week. Since product development effort is budgeted as a fraction of sales, effort rises throughout the run.[18]

The product development effort leads to design improvements that increase the product quality. As these design improvements are incorporated at the production level and are observed by the market, the accepted product quality (APQ) rises. The rise in accepted product quality creates an almost linear increase in potential demand from week 130 to week 650. After week 650 the increases in accepted product quality result in only fractional increases in potential demand.

Order rate builds up much more slowly than potential demand. When potential demand first begins to rise about week 104, the company is able to fill the orders out of inventory. However, with the company unable to bring new capacity into operation for 104 weeks, inventories are soon depleted and a backlog of unfilled orders (UFO) accumulates. The subsequent rise in delivery delay is observed by the market about week 143. Consumers, unwilling to accept the long

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[18] The plausibility of not reducing product development effort as a fraction of sales as the maximum quality is approached may be questioned although competitive pressures to make continuous design changes frequently make it necessary to carry on an extensive development effort (continued next page)

delivery delay, withhold purchases. Thus, in spite of a rising potential demand, between week 143 and week 156 order rate actually declines. The decline in order rate slows the accumulation of unfilled orders as well as the lengthening of delivery delay.

The feedback between order rate, unfilled orders, delivery delay, and production capacity creates an oscillation in production capacity orders. The initial rise in order rate is projected 130 weeks into the future causing a rapid rise in the production capacity order. However, when the company sees order rate declining about week 143, it thinks it has overestimated the future growth in order rate. Thus, in spite of an excessive backlog and a low inventory, the company orders no production capacity between weeks 156 and 182. About week 180 the production capacity ordered during the first rise in order rate comes into operation. This along with the rise in potential demand creates a second rise in order rate. Again the company projects the growth into the future and increases its production capacity order. However, because the company had curtailed its order for production capacity earlier, no more capacity can be brought into operation and the growth in order rate is slowed because of a rising delivery delay. As before, seeing the growth in order

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even though the design changes may result in little improvement in quality. Since the growth behavior being studied is not affected by the development effort once the maximum quality is approached, it has simply been assumed that the fraction of sales budgeted to development is held constant.

rate slowing, the company thinks it has overestimated the future growth and begins to curtail the production capacity order again. The 20% decline in the production capacity order between week 234 and week 273 is not discernible in Figure V-5.

The level of unfilled orders does not peak until week 780. However, because production capacity rises faster than backlog after week 400, the delivery delay peaks at week 403 at which time 63% of the demand is lost.

It is interesting to note the inability of this production capacity decision to order sufficient capacity. This can be explained by the interaction between the forecast of order rate, the production capacity order, the production capacity, and the delivery delay. Whenever the order rate rises above the production capacity, unfilled orders will accumulate until the delivery delay has increased to the point where order rate is depressed to the production capacity level. Since the production capacity is determined by the production capacity order which in turn is based upon the forecast order rate, the order rate is determined not by the potential demand, but by the forecast order rate through its influence on the production capacity.[19]

Run number 1 using the passive development policy was qualitatively very similar to Run 2. The observed delivery

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[19] See Nord and Swanson for a more complete discussion of this production capacity ordering policy, <u>op</u>. <u>cit</u>.

delay reached a maximum of 12 weeks at which time the company lost more than 45% of the demand. For 7 years the company lost more than 40% of the demand. At the end of growth the company found itself with 22% overcapacity. A total of 3,478,000 orders were received.

In run number 3 using the aggressive development policy the delivery delay reached a maximum of 18 weeks at which time the company lost 75% of the demand. For four years the company lost over 70% of the demand. Projecting the order rate beyond the saturation level and ordering capacity to adjust unfilled orders and inventory left the company with 25% overcapacity at the end of growth. A total of 4,786,000 orders were received during the run.

In Figure V-6 the growth of order rate in runs 1, 2, and 3 is shown As can be seen, doubling or halving the fraction of sales budgeted to product development results in an almost identical growth. By doubling the fraction of sales budgeted to development the company received only 12% more orders or by halving the fraction of sales budgeted to development it received only 20% fewer orders. The major difference between the growth patterns is a time delay.

<u>Sufficient Production Capacity</u> In runs 4, 5, and 6 all model parameters were held constant except for the product development policy. All three runs were characterized by

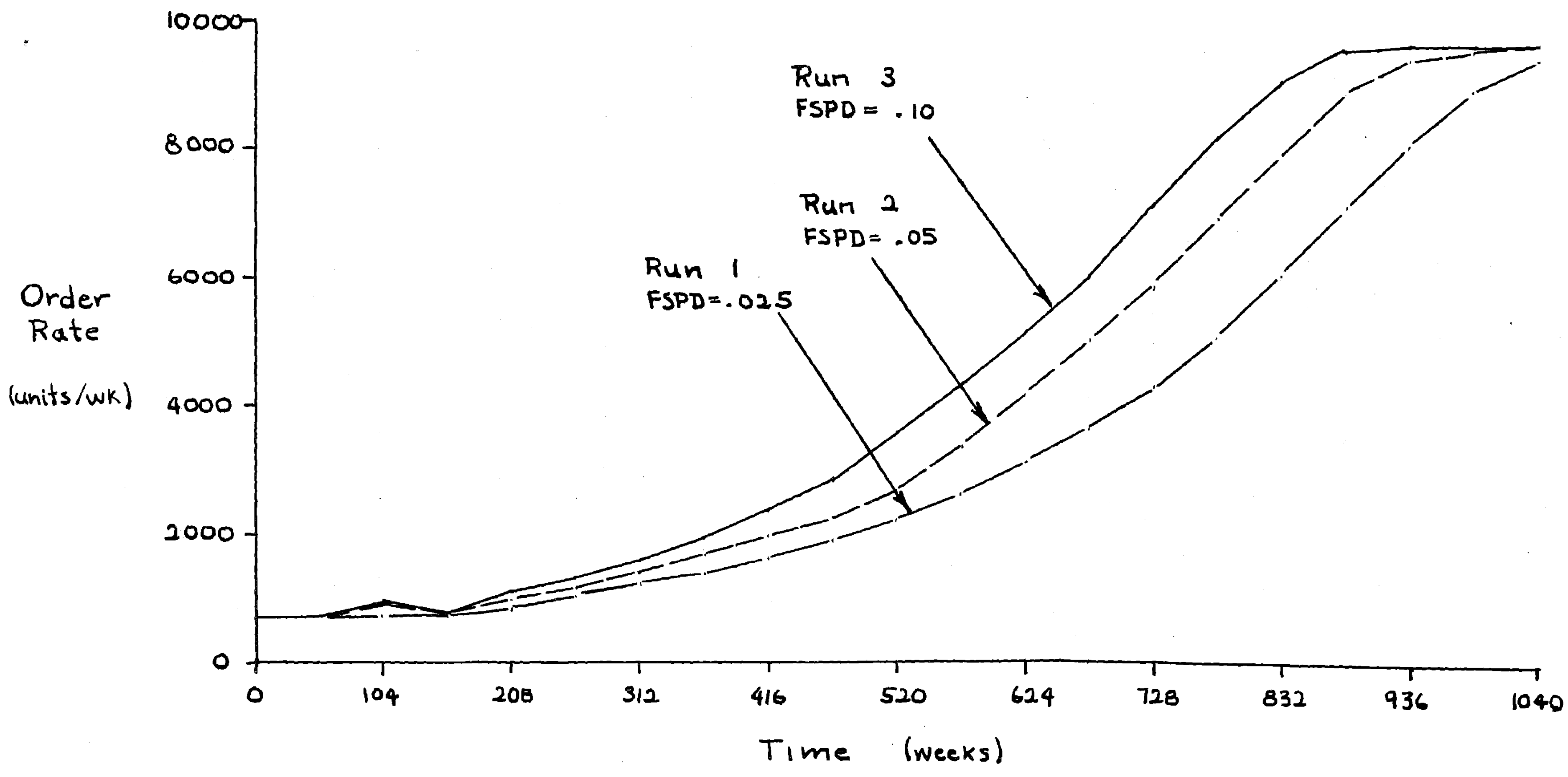

Figure VI-6 The Growth of Order Rate for Runs 1, 2, and 3.

a short delivery delay and an order rate that followed potential demand very closely. Since the qualitative behavior of the model was the same for all three runs, only run 5 will be discussed in detail.

Run number 5 using the average development policy is shown in Figure V-7. The observed delivery delay rises to a maximum of only 5 weeks. At no time during the run does the company lose more than 10% of the demand. Less than 2% excess capacity exists at the end of growth. The company received a total of 5,723,000 orders during the run.

The rise in accepted product quality creates an almost linear increase in potential demand between week 260 and week 600. Since the observed delivery delay is short throughout the run, the order rate has an almost identical growth pattern.

Again we find a small oscillation in the delivery delay and in the production capacity order. As before, this oscillation arises from the feedback between unfilled orders, observed delivery delay, order rate, and production capacity order. An increase in order rate is amplified in the production capacity decision. When the rise in order rate is curtailed by the mounting delivery delay, the company thinks is has overestimated the growth in order rate and reduces its production capacity order. Then as the potential demand and the new production capacity being brought into operation

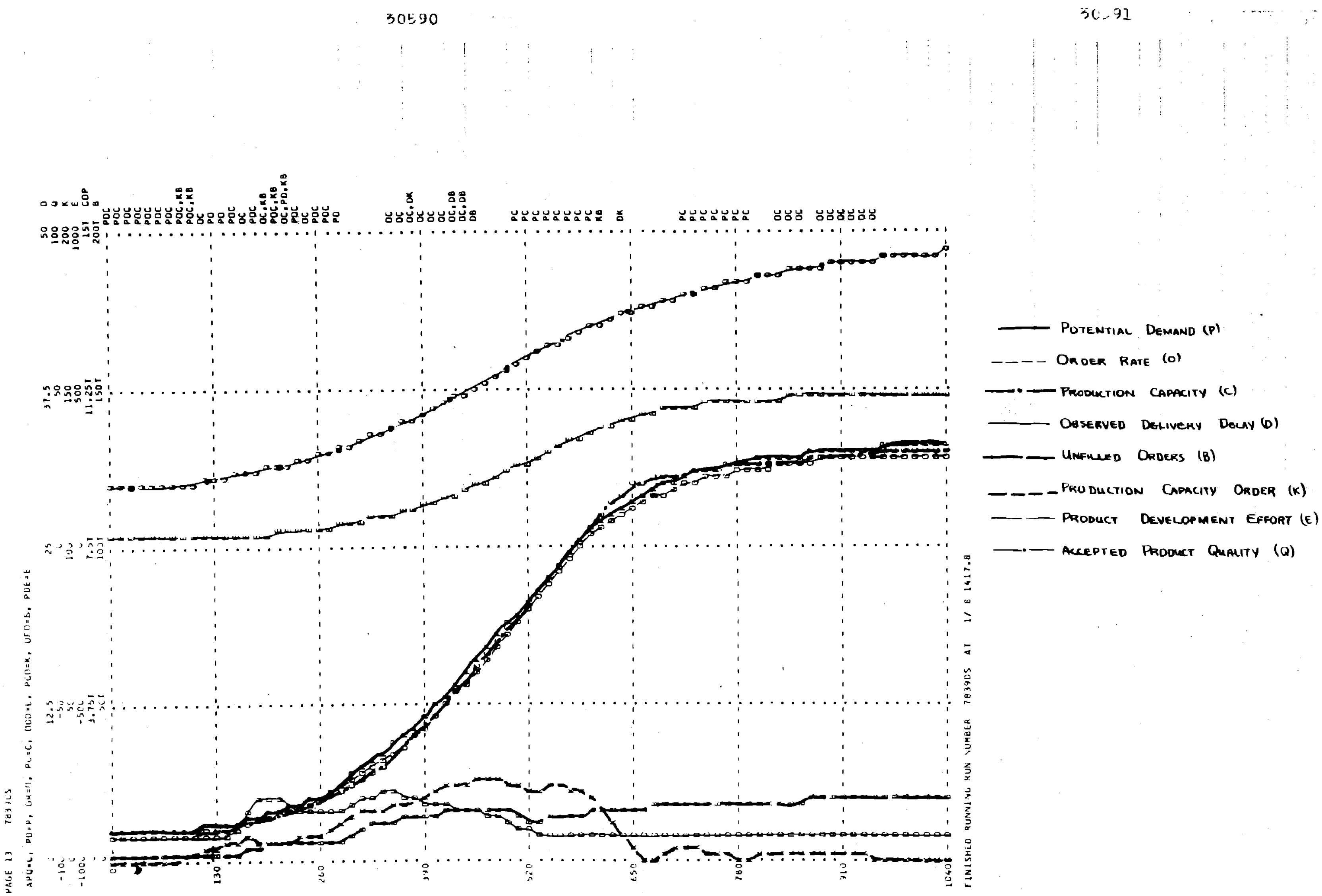

Figure V-7 Run Number 5.

generate a further growth in order rate, the production capacity order is increased again.

The period of the oscillation in this run is longer than the period of oscillation in run 2 because of the implicit delay in loop 2. Under the assumed relationship between the delivery delay and the delivery delay multiplier, when the delivery delay is short it takes a longer time for an increase in order rate to cause a given decrease in the delivery delay multiplier.

The oscillation that occurs in the production capacity order after week 650 cannot be attributed to the feedback between unfilled orders, observed delivery delay, order rate, and production capacity order since the observed delivery delay is at a minimum from week 520 to the end of the run. Instead, the oscillation arises from linearly extrapolating the order rate when the growth rate is declining. Just before week 650 the growth of order rate begins to slow. However, because a linear extrapolation of order rate assumes no decline in the growth rate, the forecast order rate causes the company to overestimate capacity needs. Later, when the company finds itself in a temporary position of overcapacity, the production capacity order is curtailed until the excess capacity is worked off by the growth of order rate. Then again the company overestimates its capacity needs by linearly extrapolating order rate. When the company realizes its mistake, it curtails the production capacity order a second time.

The model behavior in runs 4 and 6 were qualitatively the same as in run 5. In run 4 the company never lost more than 3% of the demand. A total of 4,307,000 orders were received.

Although in run 5 the company did lose as much as 20% of the demand for a short time, order rate still followed demand very closely. A total of 6,616,000 orders were received.

In Figure V-8 the growth of order rate for runs 4, 5, and 6 is shown. As expected, the growth of order rate is more sensitive to the fraction of sales budgeted to product development in this situation than when growth is characterized by a production capacity insufficient to satisfy demand. Whereas the company received only 12% more orders using the aggressive development policy in the 1st set of runs, in this set of runs at week 520 when the order rate begins to saturate in run 6, the company receives 50% more orders with the aggressive policy than with the average policy, or in the first set of runs only 20% fewer orders were received using the passive policy instead of the average policy while in this set of runs at week 676 when the order rate begins to saturate in run 5, the company receives 50% more orders with the average policy than it receives with the passive policy.

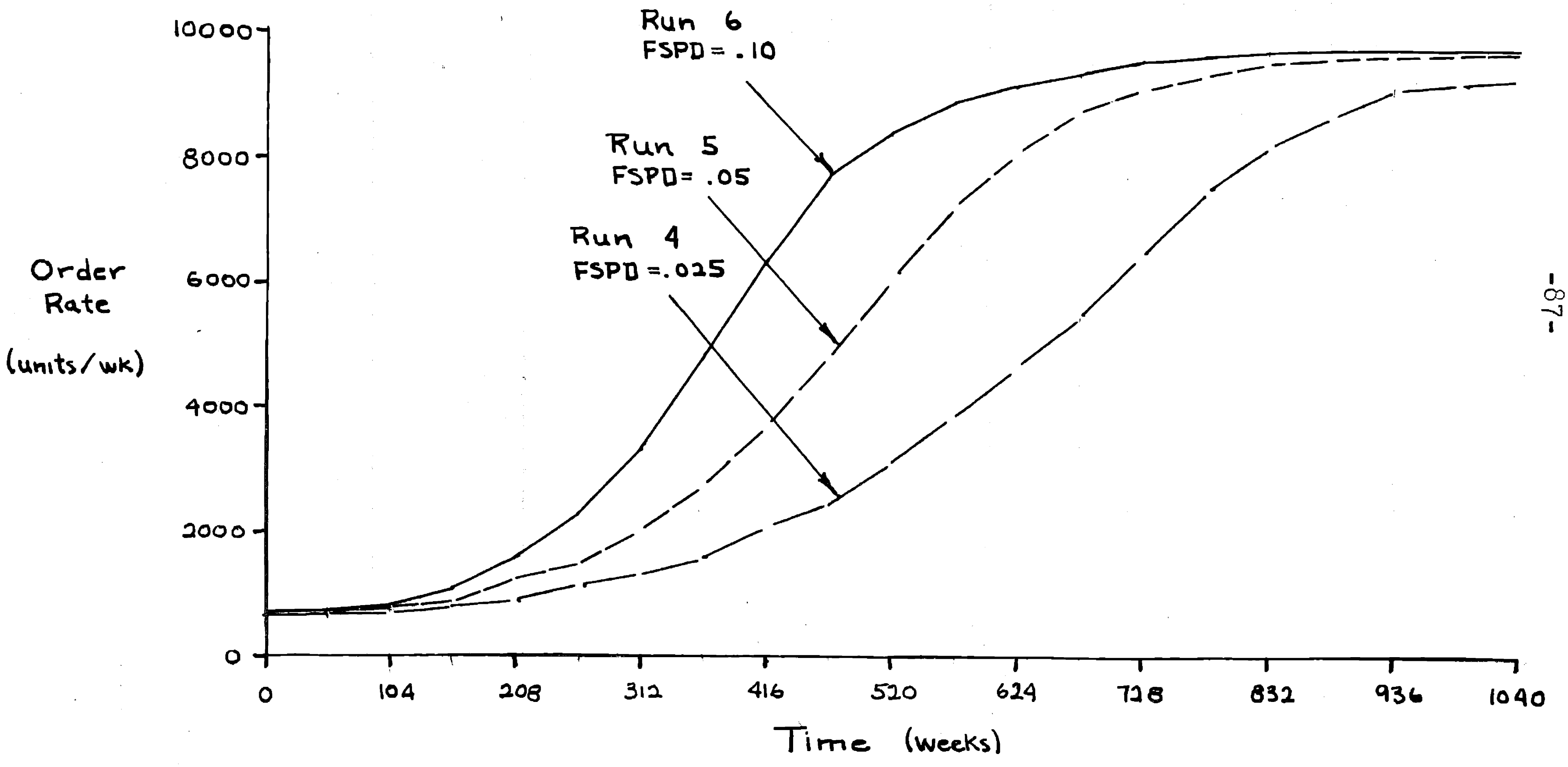

Figure V- The Growth of Order Rate for Runs 4, 5, and 6.

While runs 4, 5, and 6 show that growth is more sensitive to the development policy when production capacity is sufficient to satisfy demand, the difference was not as great as expected. The growth rates varied more in timing than in magnitude. This is particularly true of the growth rates for the aggressive policy and the average policy. Doubling the fraction of sales budgeted to development resulted in an almost identical growth rate with a lead of less than 104 weeks.

A more detailed analysis of runs 4, 5, and 6 revealed why the growth rates differed much less than would be expected from a comparison of the development policies. The more aggressive policy by creating a more rapid development increased the difference between the product quality at the development level and the product quality accepted in the market. Consequently, the potential demand is lower at every stage of development for the more aggressive policy. The lower demand partially offsets the higher fraction of sales budgeted to development and, hence, the development rates differ much less than a comparison of the development policies might lead one to believe.

A comparison of the development effort a various levels of product quality for runs 4, 5, and 6 is shown in Figure V-9. Only at time zero is the product development effort proportional to the fraction of sales budgeted to development.

When the product quality development is 60, using the aggressive policy instead of the average policy results in only a 33% increase in product development effort, or using the aggressive policy instead of the passive policy results in only a 66% increase in product development effort.

	PDE at PQD=20 (time=0)	PDE at PQD=40	PDE at PQD=60	PDE at PQD=80
Run 4 FSPD = .025	17.5	29	61.6	110.5
Run 5 FSPD = .05	35	35	85.5	150.0
Run 6 FSPD = .10	70	70	103.5	190.2

FSPD - Fraction of Sales budgeted to Product Development (dimensionless)

PDE - Product Development Effort (manhours/week)

PQD - Product Quality Development (quality units)

Figure V-9 The Product Development Effort at Various Levels of Product Quality Development.

<u>Altering the Delay in Loop 3</u> The detailed analysis of runs 4, 5, and 6 lead to two hypotheses: 1) When the overall time required for development is long relative to the delay in the feedback between product development effort and order rate (loop 3), at various levels of product quality the potential demand will differ less for the three development policies, and, hence, the development efforts will more closely

approach those indicated by the development policies; growth will be more sensitive to the development policy, 2) When the overall time required for development is short relative to the delay between the creation of quality and the acceptance of quality, growth will tend to be limited by the rate at which quality can be incorporated at the development level and the rate at which quality is accepted by the market; growth will be less sensitive to the development policy.

Runs 7, 8, 9, and 10 were designed to test the former hypothesis. Figure V-10 shows the ratio of the product development effort for the aggressive policy to the product development effort for the passive policy at different levels of product quality for a 338 week delay in the loop and for a 130 week delay in the loop. Only at PQD = 40 is the ratio of the product development effort for the aggressive policy to the product development effort for the passive policy less for the 130 week delay than for the 338 week delay.[20] It may be concluded, therefore, that growth will be more sensitive to the development policy when the feedback between product development effort and order rate is shorter relative to the overall time required for development.

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[20] At PQD ≠ 40 the ratio of the efforts is greater for the 338 week delay than the 130 week delay because of the shape of the potential demand curve. For the 338 week delay the difference between the product quality at the development level and the product quality accepted in the market covers a less elastic portion of the potential demand curve.

	Ratio of PDE for FSPD=.10 to PDE for FSPD=.025 at			
	PQD=20 (time=0)	PQD=40	PQD=60	PQD=80
Loop 3 338 weeks	4	2.62	1.85	1.78
Loop 3 130 weeks	4	2.50	2.34	3.99

PDE - Product Development Effort (manhours/week)

FSPD - Fraction of Sales budgeted to Product Development (dimensionless)

PQD - Product Quality Development (quality units)

Figure V-10 A Comparison of the Development Effort with a Varying Delay in Loop 3.

Runs 11, 12, and 13 were designed to test the hypothesis that growth would be less sensitive to the development policy when the overall time required for development is long relative to the delay between the creation of quality and the acceptance of quality.

All three runs were characterized by a low delivery delay and a production capacity sufficient to satisfy demand. The growth of order rate for the three runs is shown in Figure V-11.

A comparison of Figure V-11 and Figure V-8 shows that the model is less sensitive to the development policy when the overall time required for development is shorter relative to the lead-time and the delay for observing and accepting quality. Figure V-12 shows quite clearly why this is true.

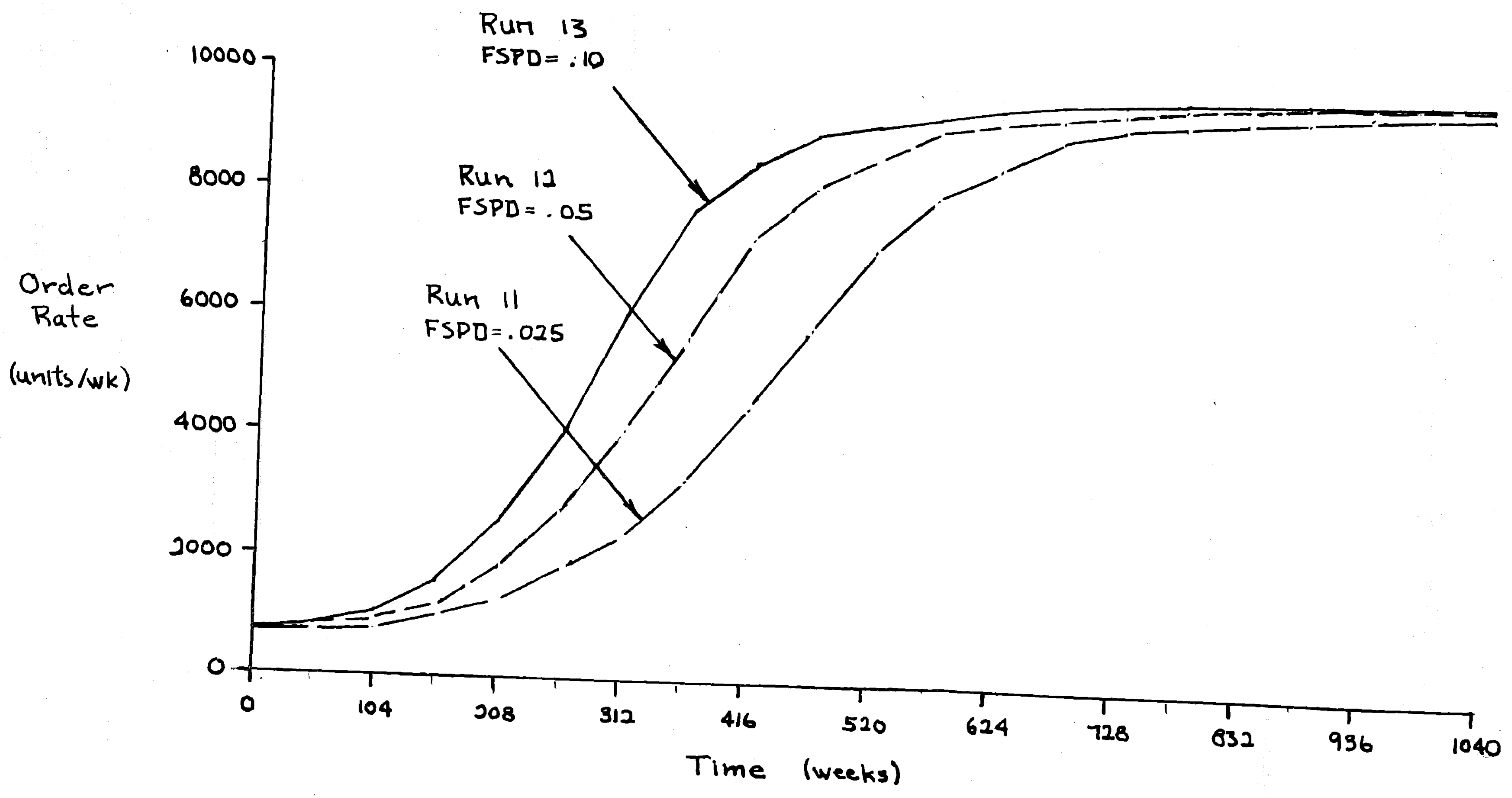

Figure V-11 The Growth of Order Rate for Runs 11, 12, and 13.

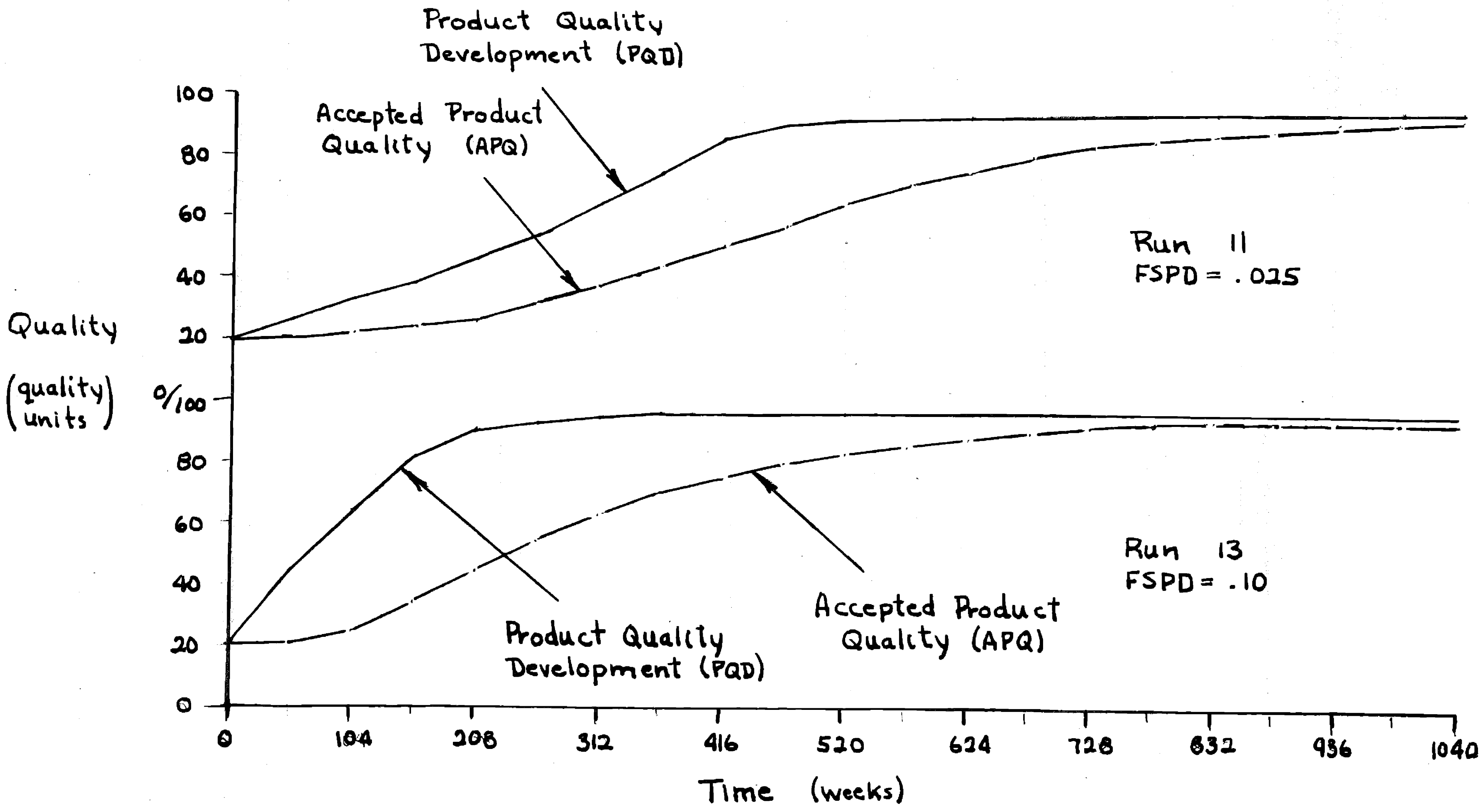

Figure V-12 The Growth of Quality for Runs 11 and 13.

With the aggressive policy the product quality at the development level builds up very rapidly. However, much of the rapid growth is lost because of the smoothing effect of the long delay between the creation of quality and the acceptance of quality by the market. Growth tends to be limited by the rate at which product quality can be incorporated at the production level and the rate at which quality is accepted by the market.

With the passive policy there is much less smoothing of the growth rate. Instead we find the growth rate of the accepted product quality and the growth rate of the product quality development differ very little.

Altering the Amplification in the Product Development Effort It was initially expected that in some situations the growth of order rate would be sensitive to the amount of amplification in the product development effort. The sensitivity of the model to growth was examined for a short delay in the feedback between product development effort and for a long delay in the feedback between product development effort and order rate. In both instances growth was found to be insensitive to the amount of amplification in the development policy.

The amount of amplification in the product development policy was altered by setting the forecast time development equal to the delay for adjusting product development effort in runs 14 and 16 and by setting the forecast time development equal to the delay in adjusting product development effort plus the lead-time for runs 15 and 17. This gave a forecast time development for runs 15 and 17 exactly double the forecast time development for runs 14 and 16. The growth of order rate for these four runs is shown in Figure V-13.

In runs 14 and 15 the delay in the feedback loop between development effort and order rate was 338 weeks while in runs 16 and 17 the feedback loop between development effort and order rate was only 130 weeks. As can be seen from Figure V-13, in both instances growth was insensitive to the amount of amplification in the development policy.

Sensitivity to External Disturbances

A number of runs were made to test the sensitivity of the system to external disturbances. However, because the qualitative behavior of the system did not differ among many of these runs, only four runs will be discussed. No runs testing the sensitivity of the model to unexpected declines in product quality will be discussed since they illustrate no model behavior that is not better illustrated with a noise disturbance or with a fluctuating disturbance.

Figure V-14 gives the parameters of the runs that will be discussed. Since it was realized that the model would be less likely to amplify external disturbances when the delay in the feedback between product development effort and order

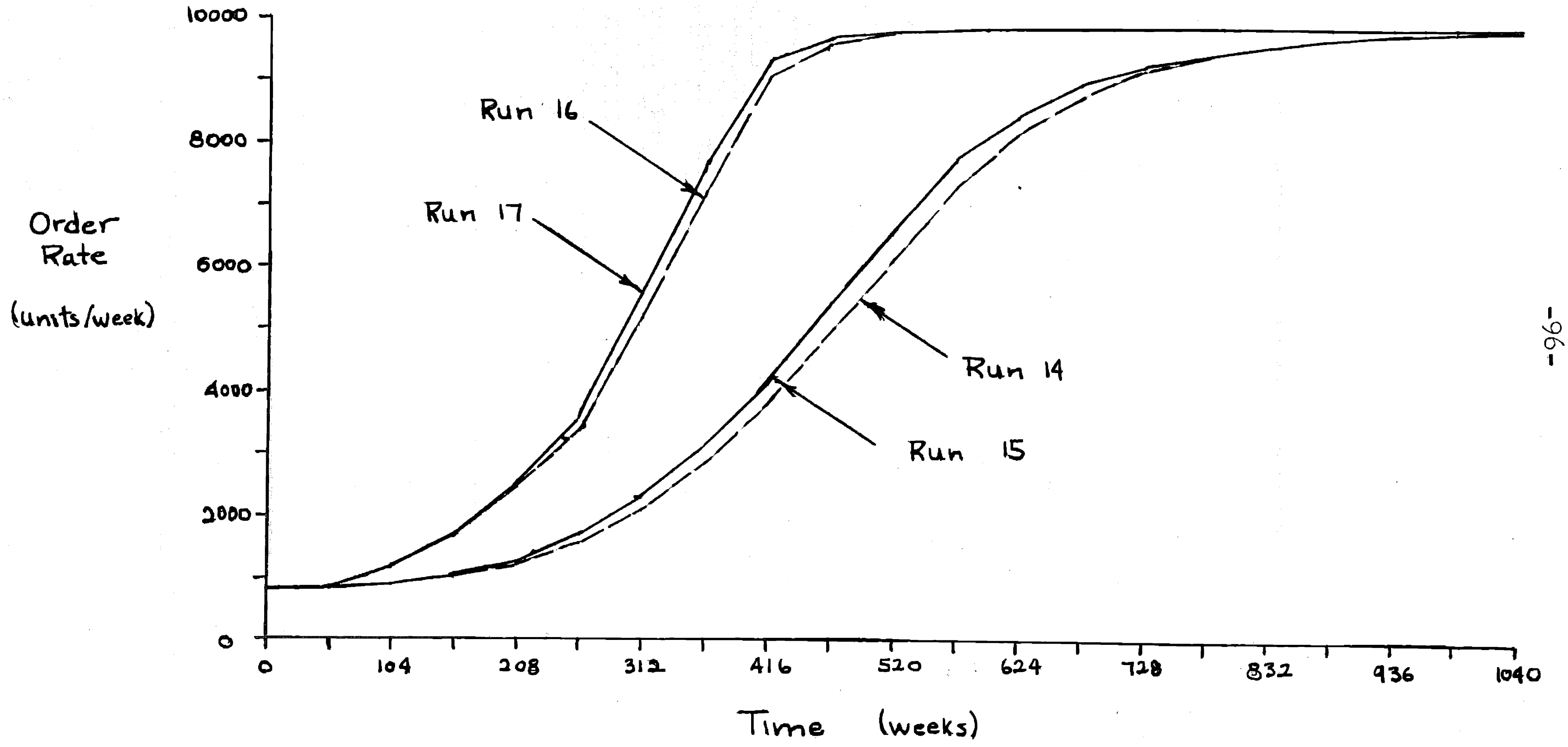

Figure V-13 The Growth of Order Rate for Runs 14, 15, 16, and 17.

rate was long, for all runs discussed the delay in adjusting product development effort and the lead-time were reduced to 26 weeks and the delay in observing and accepting quality was reduced to 52 weeks.

Set	Run	FSPD	DOAQ	DRIC	TAOC	TOPC	Disturbance
5--- To Determine Sensitivity for Insufficient Capacity							
	18	.025	52	104	52	52	Noise
	19	.025	"	"	"	"	Fluct
6 -- To Determine Sensitivity for Sufficient Capacity							
	20	.025	52	26	26	26	Noise
	21	.025	"	"	"	"	Fluct

FSPD - Fraction of Sales budgeted to Product Development (dimensionless)

DOAQ - Delay in Observing and Accepting Quality (weeks)

DRIC - Delay in Receiving and Installing Capacity (weeks)

TAOC - Time to Adjust unfilled Orders Capacity (weeks)

TOPC - Time to Order Production Capacity (weeks)

Figure V-14 Computer Runs to Test Sensitivity of Model to External Disturbances.

Insufficient Production Capacity The model was tested to determine its sensitivity to low frequency noise, to low frequency fluctuations, and to unexpected declines in product quality. It was found to be insensitive to all three types of external disturbances.[21]

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[21] This simply confirms the findings of Nord and Nord and Swanson.

Run 18 is shown in Figure V-15. The external input was a normally distributed random variable sampled every 52 weeks with a standard deviation of 0.20. The observed delivery delay reaches a maximum of 16 weeks at which time the company loses 65% of the demand. For over ten years the company loses more than 50% of the demand. At the end of the run the company has on order and in operation 40% more capacity than is needed. Most of this is ordered from projecting the growth of order rate beyond the saturation level during the rapid growth around week 780 and during the rapid growth just after week 910.

It is interesting to note the almost complete insensitivity of growth to the external disturbance. From week 130 to week 780 growth is accompanied by a long delivery delay that insulates the system from the disturbance. An externally induced increase in order rate is quickly suppressed by the market reacting to a longer delivery delay by placing fewer orders. Similarly, an externally induced decrease in order rate is suppressed by the market reacting to a shorter delivery delay by placing more orders.

Product development effort shows no tendency to oscillate until after market saturation and the rise in accepted product quality is smooth and continuous.

Throughout the run production capacity orders fluctuate up and down almost randomly. If unfilled orders showed any oscillatory behavior, we might attempt to link these oscillations to the feedback between delivery delay, unfilled

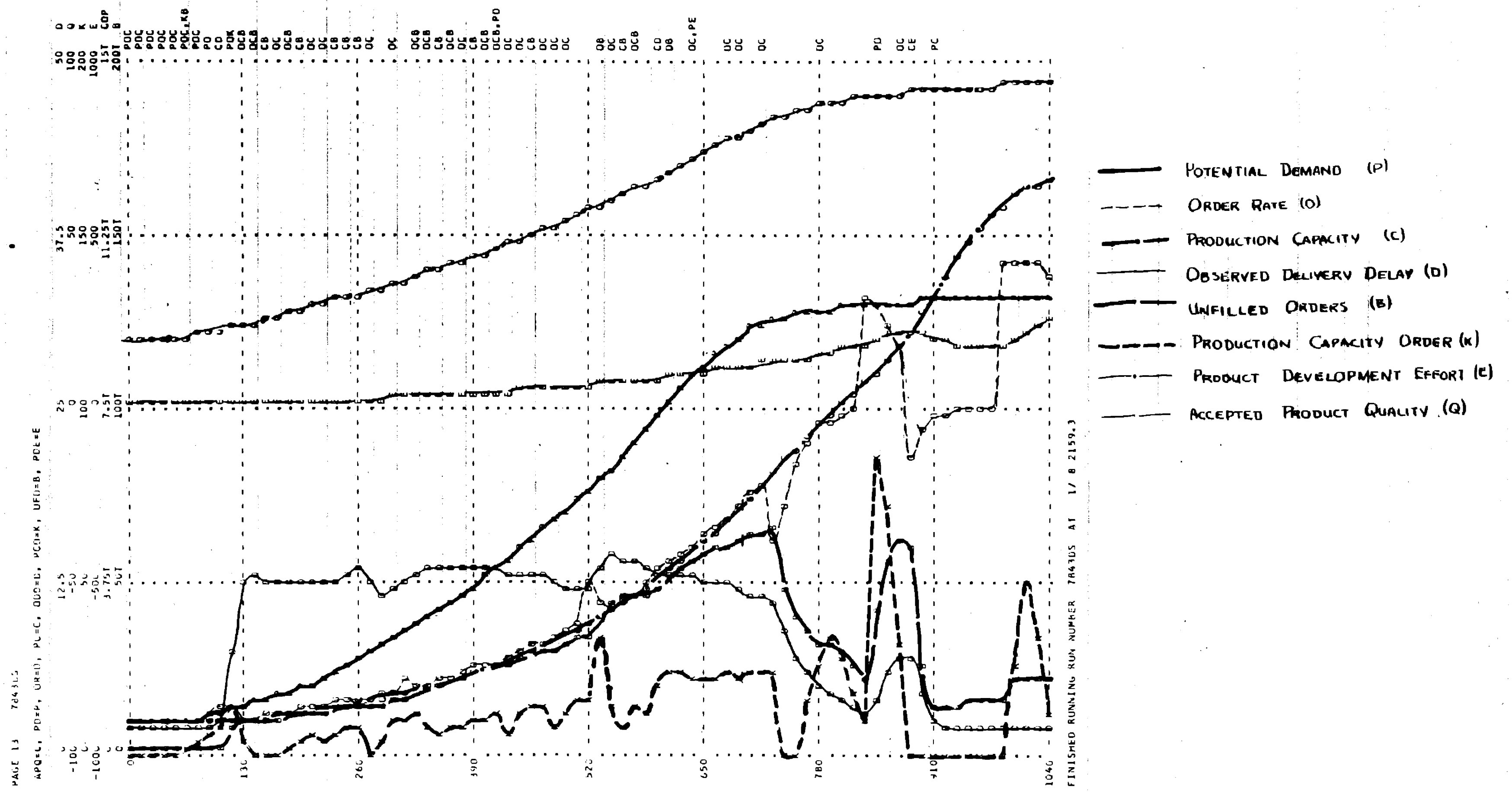

Figure V-15 Run Number 18.

orders, and order rate. However, since no oscillations occur in unfilled orders, the fluctuations in production capacity orders must be attributed to the amplification in the production capacity decision. For example, projecting the sharp rise in order rate that occurs about week 520, the company places a large order for capacity. Later when it realizes the rise was only temporary, the production capacity order is reduced.

The time behavior of order rate and the fluctuation induced in the development effort after week 780 might lead one to expect a feedback in the system to be causing the oscillation in order rate. However, since potential demand and observed delivery delay are both constant after week 780, the oscillation in order rate can only arise from the external input.[22] This simply points out how easily a company might perceive a non-existent seasonality in the demand for one of its products.

Figure V-16 shows the external disturbance, the delivery delay multiplier, and the order rate. It should be noticed that the fluctuations in delivery delay multiplier are exactly out of phase with the external disturbance. When the external disturbance causes an increase in the order rate, the delivery delay lengthens and the delivery delay multiplier multiplier decreases. When the external disturbance causes a decrease in the order rate, the delivery delay shortens and the delivery delay multiplier increases.

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[22] Order rate is equal to the product of the potential demand, the delivery delay multiplier, and the external disturbance.

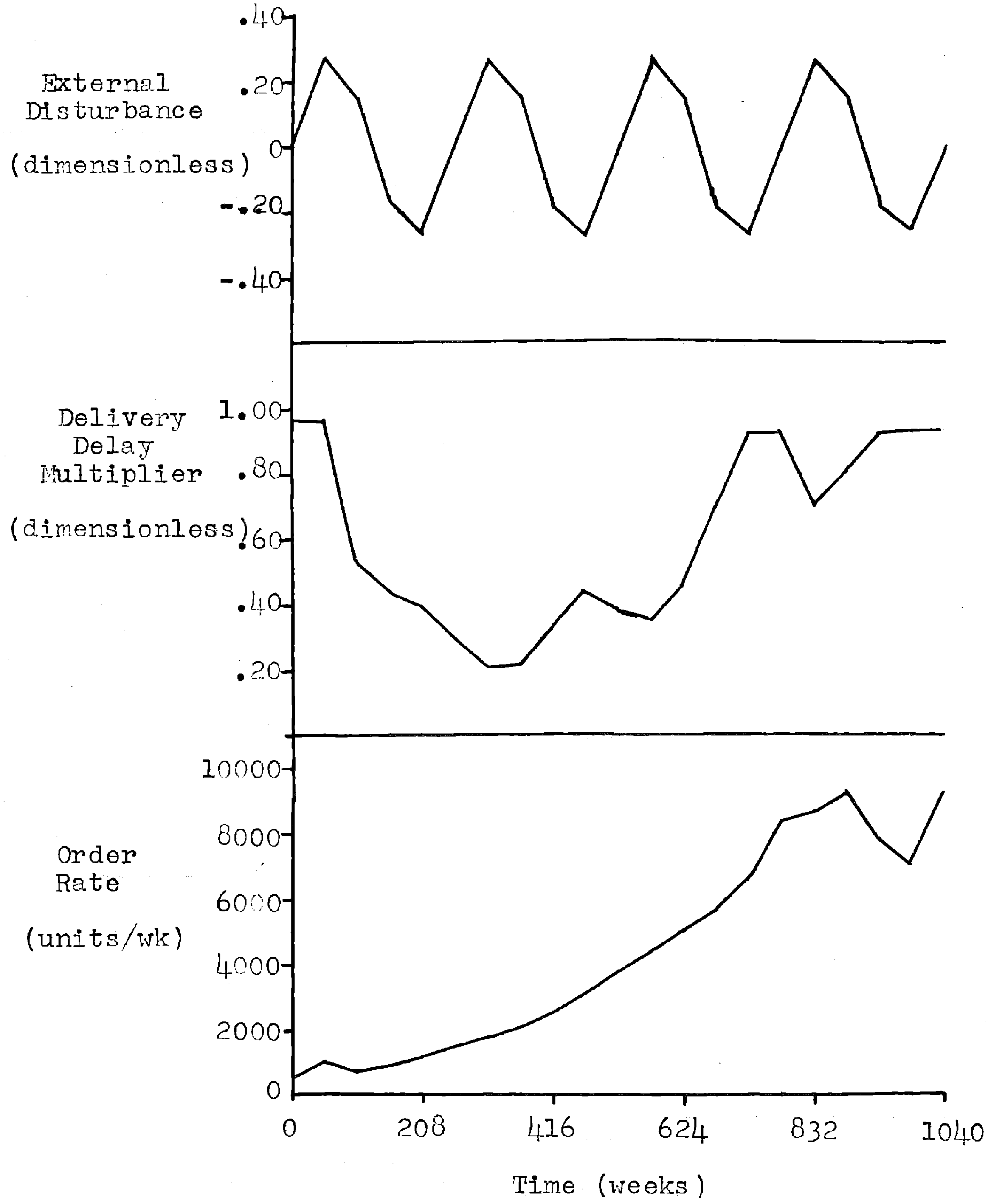

Figure V-16 The Cushioning effect of the Delivery Delay in Run 19.

Sufficient Production Capacity It had been hypothesized that the model might show some tendency to amplify external disturbances and exhibit an uneven growth rate in this growth situation. This was clearly not the case as the model was almost as insensitive to external disturbances as it was in the growth situation where production capacity was not sufficient to satisfy demand.

Run 20 is shown in Figure V-17. The external input was a normally distributed random variable sampled every 52 weeks with a standard deviation of 0.20. The observed delivery delay reaches a maximum of only 8 weeks during one of the upswings in demand. By projecting the order rate beyond the saturation level and ordering capacity to adjust unfilled orders and inventory, at the end of growth the company finds itself with 28% overcapacity. No fluctuation is induced in the product development effort and the rise of accepted product quality is smooth and continuous.

As before the delivery delay insulates the system from the external disturbance. This occurs in spite of the company being able to order sufficient capacity to satisfy demand. Temporary overexpansions that might make the system sensitive to the external disturbances are eliminated by the continuous rise in potential demand.

As in runs 1 through 6 a small oscillation arises between observed delivery delay, order rate, and production capacity

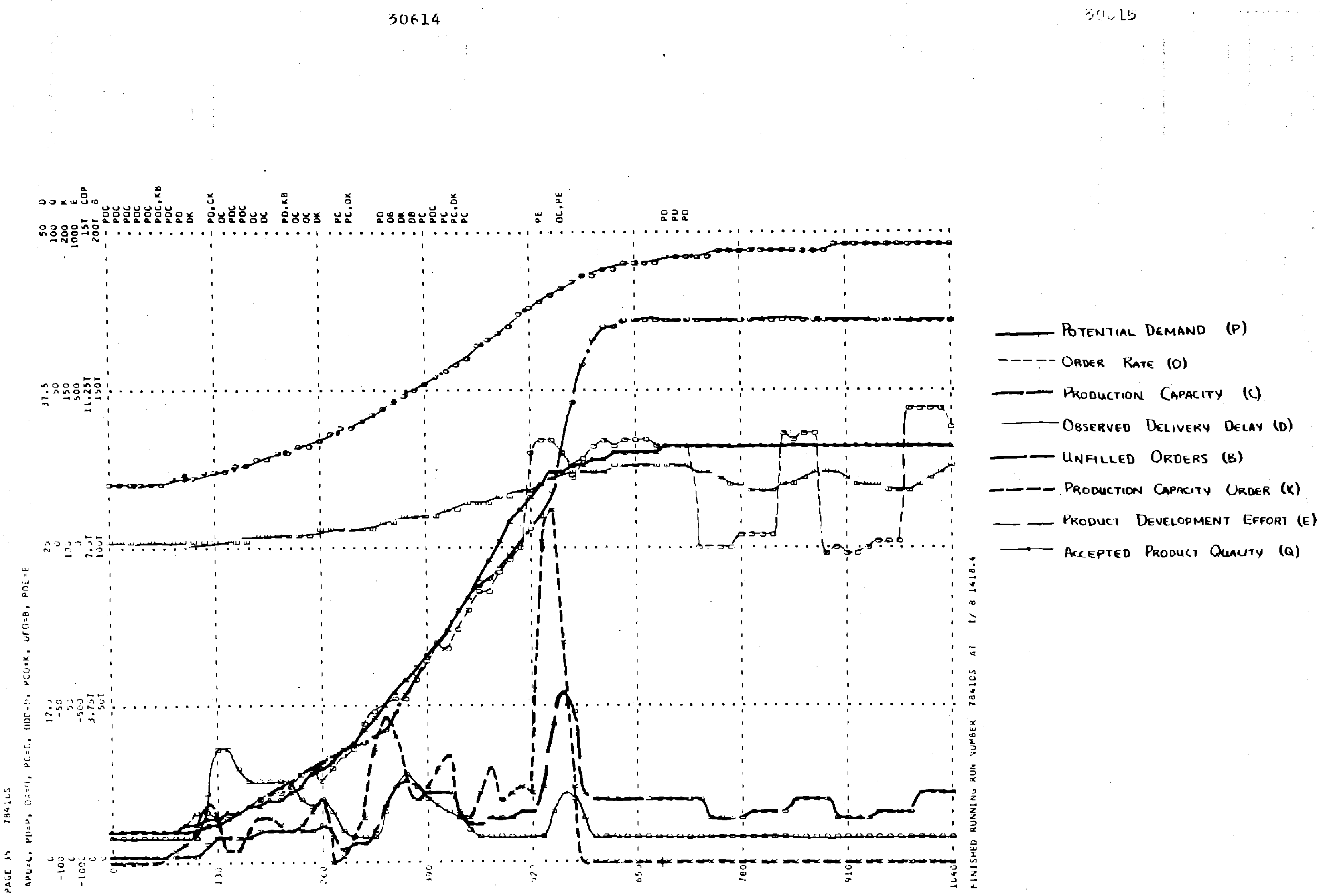

Figure V-17 Run Number 20.

orders. An increase in order rate is amplified in the production capacity decision. At the same time the increase in order rate increases the delivery delay which in turn depresses the order rate. When the company sees that the rise is only temporary, the production capacity order is reduced. Meanwhile, the production capacity ordered earlier comes into operation and reduces the delivery delay setting the stage for another rise in order rate. In the subsequent rise little capacity is brought into operation because of the earlier reduction in the production capacity order. Hence, the stage is set for another rise in delivery delay.

As in run 18, there appears to be a periodic fluctuation in order rate at the end of the run, but since both the potential demand and the delivery delay are constant, we know that this must simply be the noise from the external input.

The wide fluctuations in demand that occur after growth illustrate the sensitivity of a mature product to external disturbances. It would be reasonable to conclude that a company whose sales were concentrated in new and growing products would tend to be less sensitive to inflationary and deflationary forces in the economy than a company whose sales were concentrated in mature products.

Run 21 shows the cushioning effect of the delivery delay with a periodic fluctuation. The amplitude of the fluctuation is 0.30 and the period of the fluctuation is 260 weeks.

The order rate, the delivery delay multiplier, and the external disturbance for run 21 are shown in Figure V-18. As in run 19 the external disturbance and the delivery delay multiplier are out of phase. As would be expected, the cushioning effect of the delivery delay is not as great in this run as in run 19.

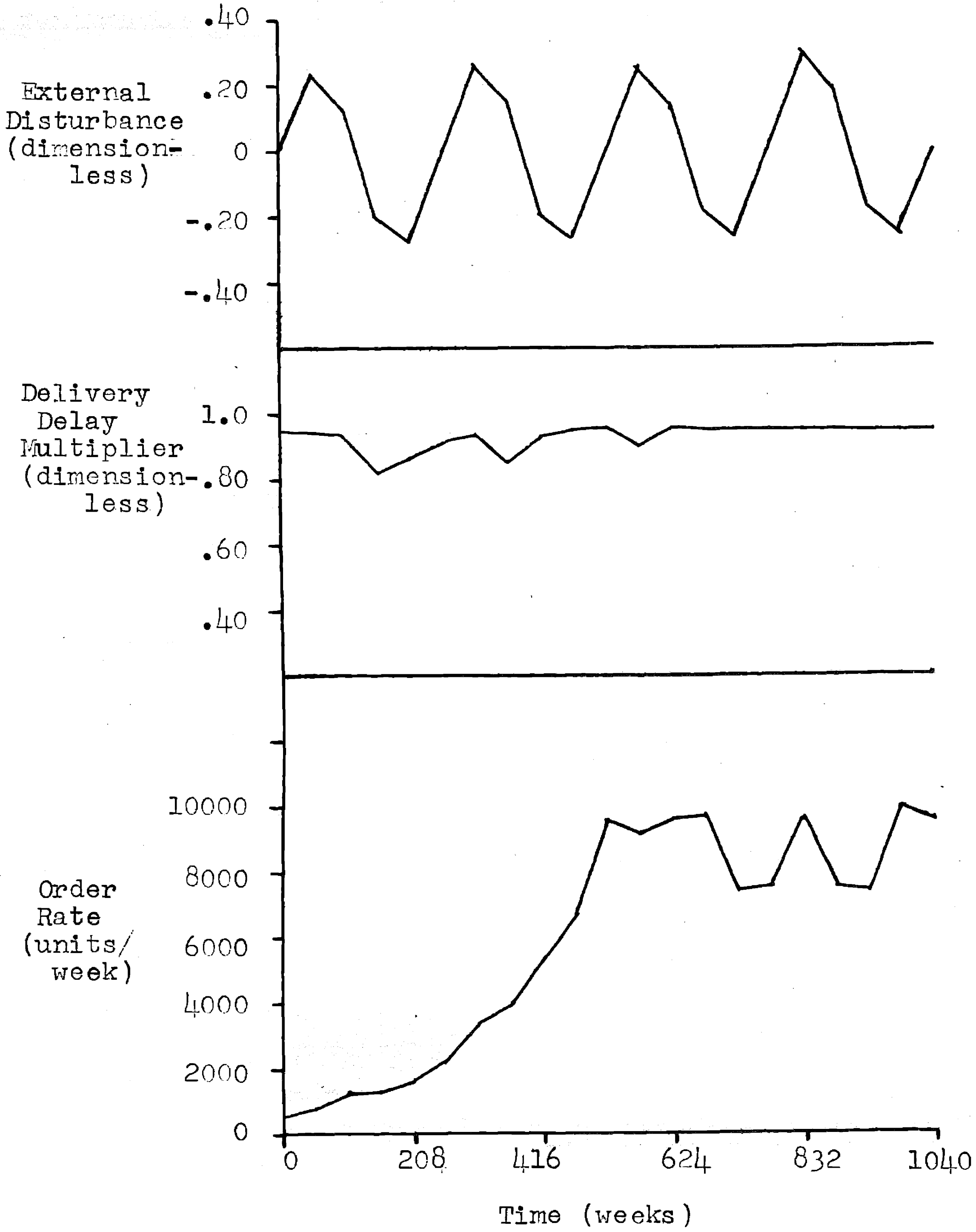

Figure V-18 The Cushioning Effect of the Delivery Delay in Run 21.

CHAPTER VI

CONCLUSION

Implications of Model Behavior

The model behavior showed that: 1) The growth of a product will tend to be insensitive to the fraction of sales budgeted to product development effort when the production capacity decision is unable to provide sufficient capacity to satisfy demand and when the overall time required for development is short relative to the length of the delay between the creation of quality and the acceptance of quality, 2) The growth of a product is unlikely to be sensitive to external disturbances when the market reacts to an increase in delivery delay by placing fewer orders.

In the growth situation where the production capacity decision was unable to to provide sufficient capacity to satisfy demand, growth was limited by the production capacity. Increasing the rate of development created a longer delivery delay that lead to a greater loss of demand which tended to offset the more rapid development created by a more aggressive development policy. To increase the growth rate in this situation, the company's attention should be focused on the production capacity decision, not on product development.

Growth was found to be less sensitive to the development policy when the overall time for development was short relative to the delay between the creation of product quality and the acceptance of product quality. This occured for two reasons. First of all, the growth rate tended to be limited by the rate at which production methods could be developed and the rate at which the quality was accepted by the market, not by the rate of development. Secondly, the positive feedback between product development effort and order rate tended to be suppressed in this stituation.

The long delay between the creation of quality and the acceptance of quality tended to smooth out the more rapid development created by a more aggressive development policy. Product quality increases could not be incorporated at the production level as fast as they were developed due to the long lead-time for developing production methods. When the product quality increases were incorporated at the production level, they were not accepted by the market as fast as they had been incorporated due to the long delay for observing and accepting quality.

A more aggressive development policy will create an earlier buildup of demand which in turn will bolster the product development effort and increase the rate of development. This is a positive feedback with an amplification directly proportional to the fraction of sales budgeted to development.

Increasing the fraction of sales budgeted to development will increase the amplification around this loop which in turn will increase the growth rate. However, when the overall time required for development is short relative to the delay between the creation of quality and the acceptance of quality, this feedback tends to be suppressed and, hence, growth becomes less sensitive to the fraction of sales budgeted to development.

The delivery delay insulated the system from external disturbances during growth. Externally induced increases in order rate were suppressed by the market reacting to a longer delivery delay by placing fewer orders. Externally induced decreases were suppressed by the market reacting to a shorter delivery delay by placing more orders.

Initially it was hypothesized that the model might be sensitive to external disturbances in the growth situation where the production capacity was able to provide sufficient capacity to satisfy demand. However, it was found that the continuous rise in product quality created an upward pressure on order rate that eliminated temporary overexpansions in capacity that would have made the system sensitive to external disturbances.

From this it may be concluded that a company whose sales are concentrated in new products will tend to be insulated from recessionary forces in the economy. Robert Sprague, president of Sprague Electric, noted that it was primarily the predominance of new products in the sales of Sprague Electric that sustained the growth of sales during the 1930 depression and saved the company from bankruptcy.[23]

The Production Capacity Problem

The long delay between the saturation of potential demand and the saturation of order rate in some of the runs pointed out the need for an effective production capacity decision. The costs of funds committed to development that yield no return for many years may severly reduce the profitability of the product. Even more costly may be the loss of market-share that may result from competitors being attracted to the market by the long delivery delay.

Two approaches may be taken to this problem. One approach is to control the development to provide a more gradual buildup of demand. The other approach is to improve the production capacity decision. Of these two approaches the latter is clearly the more desirable.

Slowing product development may attenuate the undercapacity problem, but in a competitive situation any initial lead in product quality could be quickly lost if product development were slowed. This would probably lead to a loss of market-share and, in some instances, it could lead to a loss of industry leadership.

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[23] Robert C. Sprague, "A Pioneer in Electronics in New England," Address to Newcommen Society, Boston, November 6, 1958.

Attempting to meet the problem by reducing product development effort whenever the delivery delay becomes excessive would be almost infeasible due to the long delay between product development effort and order rate. In many cases it would be many years before a corrective action initiated at the development level would affect the order rate.

Improving the production capacity decision is a much more feasible and desirable approach. Nord and Swanson were able to show that by using delivery delay information a much improved production capacity decision capacity decision could be formulated.[24]

For those products where an improved production capacity decision is still unable to provide enough capacity to satisfy demand, the company might attempt to reduce the growth rate of demand by increasing the delay in observing and accepting product quality and/or by increasing the lead-time for incorporating design changes. The delay in observing and accepting product quality could be lengthened by curtailing promotional expenditures. The lead-time could be lengthened by simply withholding design changes or by increasing the testing period for design changes. By doing more rigorous testing the company might be able to establish a reputation for reliability that would partially insulate it from the

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[24] Nord and Swanson, op. cit.

pricing competition that is likely to arise with excess capacity at the end of growth.

Applicability of Results

The results of this study should not be applied to product situations that do not fit the assumptions of the model. For example, the results of the study could be highly misleading if applied in a situation with competing companies or in a situation where the market reacts to a longer delivery delay by ordering further in advance.

The fact that growth was insensitive to the development policy in a non-competitive situation is no assurance that it will be insensitive to the development policy in a competitive situation. In the analysis we have considered a situation where altering the development policy resulted in a lead in product quality of only year as indicating a relative insensitivity to the development policy. However, in a competitive situation market-share may be very sensitive to a small lead in product quality.

All of the model results indicate an insensitivity to external disturbances. However, in a situation where the market reacted to a long delivery delay by ordering further in advance growth might be extremely sensitive to external disturbances.

Suggested Extensions of the Thesis

This thesis has carried forward the study of new product growth, but by no means has completed the study. Three possible extensions of the study are suggested here.

A very ambitious extension of the model would be to include the introductory stage in the life cycle. Much of the problem of development may not be so much in the actual magnitude of product development effort, but rather in the timing of product development effort. This would be a very difficult extension due to the predominance of intangible factors in the initial development. These are frequently difficult to isolate and quantify.

An equally ambitious extension of the study would be to add competing companies. As mentioned earlier competing companies may increase the sensitivity of growth to the development policy. If at the same time the market was made dynamic (expanding) or if the relationship between development effort and product quality was made a function of the "state of the art," growth would tend to become less sensitive to the development policy.

Finally, as a less ambitious extension, present worth concepts could be employed to evaluate the relative profitability of different development policies. If price were assumed to be constant, this would be a relatively simple extension.

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APPENDIX A

The Model Print-Out

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*      M1849-1245.DYN.TEST.1.1
NOTE
NOTE   MARKET SECTOR
NOTE
3L     APQ.K=APQ.J+(DT)(1/DOAQ)(PQ.J-APQ.J)        ACCEPT PROD QUALITY      01L
6N     APQ=20                                                               01N
C      DOAQ=156                                    DLY OBS ACCEPT QUAL      01C
59A    PD.K=TABLE(TABPD,APQ.K,0,100,10)            POTENTIAL DEMAND         02A
C      TABPD*=0/300/700/1600/3100/4700/6200/8000/9200/9800/10000            02C
13A    EOR.K=(PD.K)(DDM.K)(PQM.K)                                           03A
17R    OR.KL=(EOR.K)(1)(1)+(EOR.K)(RVOR.K)(CRVOR)+(EOR.K)(FLOR.K)(CFLR)     04R
6N     OR=700                                                               04N
C      CRVOR=0/CFLR=0                              CONST ORDER RATE         04C
59A    DDM.K=TABLE(TABDD,ODD.K,0,45,3)             DELIVERY DELAY MULT      05A
C      TABDD*=1/.98/.90/.75/.58/.40/.28/.18/.14/.10/.08/.07/.06/.05/.05/.   05C
X1     04                                                                   05C
3L     ODD.K=ODD.J+(DT)(1/TODD)(DD.J-ODD.J)        OBSERV DELIV DELAY       06L
6N     ODD=DPHM                                                             06N
C      TODD=8                                      TIME OBS DELIV DLY       06C
58A    PQM.K=TABHL(TABQM,RDOPD.K,0,1,.5)           PRODUCT QUALITY MULT     07A
20A    RDOPD.K=PDOQ.K/PD.K                         RATIO DM OBS TO POT DM   07A
C      TABQM*=0/.5/1                                                        07C
59A    PDOQ.K=TABLE(TABPD,OPQU.K,0,100,10)         POT DM OBS QUAL          08A
3L     OPQU.K=OPQU.J+(DT)(1/DOQU.J)(PQ.J-OPQU.J)   OBSV PROD QUAL USERS     09L
6N     OPQU=APQ                                                             09N
27A    DOQU.K=(INV.K/ASS.K)+TEPQ                   DLY OBS QUAL USERS       10A
C      TEPQ=26                                     TIME EVAL PROD QUAL      10C
NOTE
NOTE   ORDER FILLING SECTOR
NOTE
1L     UFO.K=UFO.J+(DT)(OR.JK-SS.JK)               UNFILLED ORDERS          11L
12N    UFO=(DPHM)(OR)                                                       11N
58A    DPH.K=TABHL(TABDP,RUOI.K,2,82,40)           DLY PROCESS HAND         12A
20A    RUOI.K=UFO.K/INV.K                          RATIO UNFIL O TO INV     12A
C      TABDP*=2/42/82                                                       12C
20R    SS.KL=UFO.K/DPH.K                           SHIPMENTS SENT           13R
6N     SS=OR                                                                13N
1L     INV.K=INV.J+(DT)(PR.JK-SS.JK)               INVENTORY                14L
12N    INV=(SS)(WINVD)                                                      14N
20A    DD.K=UFO.K/ASS.K                            DELIVERY DELAY           15A
3L     ASS.K=ASS.J+(DT)(1/DASS)(SS.JK-ASS.J)       AVE SHIP SENT            16L
6N     ASS=SS                                                               16N
C      DASS=4                                      DLY AVE SHIP SENT        16C
NOTE
-OTE   PRODUCTION SECTOR
NOTE
7A     PRD.K=AOR.K+PRDX.K                          PRODUCTION RATE DES      17A
23A    PRDX.K=(1/TAOP)(UFO.K-UFOD.K)+(1/TAIP)(INVD.K-INV.K)                 17A
C      TAOP=13/TAIP=13                             TIME ADJ UFO, INV        17C
3L     AOR.K=AOR.J+(DT)(1/DAOR)(OR.JK-AOR.J)       AVERAGE ORDER RATE       18L
6N     AOR=OR                                                               18N
C      DAOR=26                                     DLY AVE ORDER RATE       18C
12A    INVD.K=(AOR.K)(WINVD)                       INVENTORY DESIRED        19A
C      WINVD=8                                     WEEKS INVENTORY DES      19C
12A    UFOD.K=(AOR.K)(WUFOD)                       UNFILLED ORDERS DES      20A
C      WUFOD=2                                     WEEKS UNFIL ORD DES      20C
58A    FPCU.K=TABHL(TABCU,RPRDC.K,0,3,1)           FRAC PROD CAP UTIL       21A
20A    RPRDC.K=PRD.K/PC.K                          RATIO PRD TO CAP         21A
C      TABCU*=0/1/1/1                                                       21C

                                                 2
12R    PR.KL=(PC.K)(FPCU.K)                        PRODUCTION RATE          22R
7A     PCD.K=FOR.K+PCDX.K                          PRODUCTION CAP DES       23A
23A    PCDX.K=(1/TAOC)(UFO.K-UFOD.K)+(1/TAIC)(INVD.K-INV.K)                 23A
C      TAOC=52                                     TIME ADJ ORDERS CAP      23C
C      TAIC=52                                     TIME ADJ INV             23C
14A    FOR.K=AOR.K+(GROR.K)(FTP)                   FORECAST ORDER RATE      24A
C      FTP=78                                      FORECAST TIME PROD       24C
21A    GROR.K=(1/DAORP)(AOR.K-AORP.K)              GROWTH RATE ORDER RATE   25A
3L     AORP.K=AORP.J+(DT)(1/DAORP)(AOR.J-AORP.J)   AVE ORDER RATE PAST      26L
6N     AORP=OR                                                              26N
C      DAORP=52                                    DLY AVE ORD RATE PAST    26C
58A    FICD.K=TABHL(TABPC,RCDOO.K,1,21,10)         FRAC INCREAS CAP DES     27A
48A    RCDOO.K=PCD.K/(PC.K+PCOO.K)                 CP DES TO CP ORD, OP     27A
C      TABPC*=0/10/20                                                       27C
22R    PCO.KL=(1/TOPC)((FICD.K)(PCOO.K)+(FICD.K)(PC.K))      PROD CAP ORD   28R
6N     PCO=0                                                                28N
C      TOPC=52                                     TIME TO ORD PROD CAP     28C
39R    PCAR.KL=DELAY3(PCO.JK,DRIC)                 PROD CAP ADDITION RATE   29R
C      DRIC=52                                     DLY REC INSTAL PROD CAP  29C
1L     PCOO.K=PCOO.J+(DT)(PCO.JK-PCAR.JK)          PROD CAP ON ORDER        30L
6N     PCOO=0                                                               30N
1L     PC.K=PC.J+(DT)(PCAR.JK+0)                   PRODUCTION CAPACITY      31L
6N     PC=0                                                                 31N
-OTE
NOTE   DEVELOPMENT SECTOR
NOTE
21A    PDED.K=(1/CPM)(FSALE.K)(FSPD)               PROD DEVEL EFF DES       32A
C      CPM=10                                      COST/MANHOUR             32C
17A    FSALE.K=(PRICE)(AOR.K)(1)+(PRICE)(GROR.K)(FTD)+(0)(0)(0)             33A
C      PRICE=10                                    PRICE/UNIT               33C
C      FSPD=.05                                    FRACT SALE PROD DEV      33C
C      FTD=52                                      FORECAST TIME DEV        33C
3L     PDE.K=PDE.J+(DT)(1/DAPDE)(PDED.J-PDE.J)     PRODUCT DEV EFFORT       34L
46N    PDE=(OR)(PRICE)(FSPD)/((CPM)(1)(1))                                  34N
C      DAPDE=52                                    DLY ADJ DEV EFFORT       34C
20R    PQDC.KL=PDE.K/EPQC.K                        PROD QUAL DEV CHNG       35R
6N     PQDC=0                                                               35N
59A    EPQC.K=TABLE(TABEC,PQD.K,0,100,5)           EFF/QUAL CHANGE          36A
C      TABEC*=200/210/220/235/250/270/290/315/340/370/400/435/470/510/550   36C
X1     /620/680/780/2000/20000/400000                                       36C
1L     PQD.K=PQD.J+(DT)(PQDC.JK+0)                 PROD QUAL DEVEL          37L
6N     PQD=20                                                               37N
21R    PQPC.KL=(1/LT)(PQD.K-PQP.K)                 PROD QUAL PROD CHANG     38R
C      LT=52                                       LEAD TIME                38C
1L     PQP.K=PQP.J+(DT)(PQPC.JK+0)                 PRODUCT QUAL PROD        39L
6N     PQP=PQD                                                              39N
17A    PQ.K=(PQP.K)(CNVPQ)(1)+(PQP.K)(RVPQ.K)(CVPQ)+(0)(0)(0)               40A
C      CNVPQ=1/CVPQ=0                                                       40C
43A    RVOR.K=SAMPLE(RNOR.K,SIOR)                  RANDOM VAR ORDER RATE    41A
C      SIOR=13                                     SAMPLING INTERVAL        41C
34A    RNOR.K=(1)NORMRN(MROR,STDRO)                RANDOM NUM ORDER RATE    42A
C      MROR=0/STDRO=.20                            MEAN, STD DEV RAN NUM    42C
31A    FLOR.K=(AFOR)SIN((2PI)(TIME.K)/PFOR)        FLUCTUATIONS ORDER RATE  43A
C      AFOR=.30/PFOR=520                           AMPL, PERIOD FLUCT       43C
59A    RVPQ.K=TABLE(TABVQ,RNPQS.K,-50,50,10)       RAN VAR PROD QUAL        44A
C      TABVQ*=1.0/1.0/.99/.98/.97/.96/.94/.91/.86/.75/.40                   44C
43A    RNPQS.K=SAMPLE(RNPQ.K,26)                   RAN NUM SAMPL PQ         45A
33A    RNPQ.K=(100)NOISE                           RAN NUM PROD QUAL        46A
```

FIGURE A-1 The Model Print-out.

APPENDIX B

The DYNAMO Equation Structure

This appendix has been added to provide a further explanation of the equation structure of the model. The particular advantages of DYNAMO are noted and the sequential solution of the equations explained. In addition, there is a brief discussion of the exponential delays employed in model building.and a brief discussion of flow diagrams.

DYNAMO is a compiler program developed at M.I.T. for simulating the behavior of industrial and economic systems. It was originally written for the IBM 704, but has since been adapted to the IBN 709 and the IBM 7090. The two principal advantages of DYNAMO are that models are relatively simple to construct in DYNAMO and models expressed in DYNAMO are relatively simple to understand--even to one who is not familiar with DYNAMO. In addition, DYNAMO has many other advantages that make it particularly well adapted for industrial dynamics models.

The model is represented by a set of equations describing the relationships existing in the system. Variables of the system are denoted by five or less alphabetical letters. These letters are chosen so the variable is easily recognizable from the letter denotation. Inventory, for example, might be represented by INV, or production rate might be represented by PR.

The set of equations is solved at constant intervals of time. Successive computing intervals are represented by

.J, .K, and .L. The current computing interval is .K; the computing interval one DT in the past is .J; and the computing interval one DT in the future is .L. Hence, INV.J is the inventory level one DT in the past and INV.K is the current inventory level. PR.JK is the production rate between the intervals .J and .K; PR.KL is the production rate between the intervals .K and .L.

The selection of the solution interval DT is at the discretion of the model builder. However, it must be short enough so that the model builder will accept constant rates of flow between computing intervals as a representation of the continuously varying flows in the real system.

Equations are classified as levels, rates, and auxiliaries. Levels are net accumulations in the system. Thus the inventory at time .K (INV.K) will be equal to the inventory at the previous computing interval .J (INV.J) plus the net accumulation between .J and .K.

INV.K = INV.J + (DT)(UR.JK - US.JK)

INV - INVentory (units)

UR - Units Received (units/week)

US - Units Shipped (units/week)

Rates are decision functions that control flows in the system. Decision functions may be either overt or implicit. An overt decision is one that is consciously made by the organization or by the market. The hiring and firing of employees, the budgeting of funds, and the purchase of capital equipment are all examples of overt decisions. Implicit decisions are made as a result of conditions existing in the system. The decision to hire new employees will be an overt decision, but the rate at which new employees are added to the labor force will be an implicit decision dependent upon the availability of new employees. The decision to budget funds for the development of a product is an overt decision, but the rate at which development will be undertaken will be an implicit decision dependent upon the availability of employees in the development department.

Rate equations are given two time notations. The rate between the solution intervals .J and .K is denoted by .JK. The rate between the solution intervals .K and .L is denoted by .KL. Rates are determined for .KL on the basis of levels at time .K. The hiring rate, for example, would be dependent upon the sales level and the labor force.

HR.KL = (SALE.K/PMH - LF.K)/DALF

HR - Hiring Rate (manhours/wk/wk)

SALE - SALEs level (units/week)

PMH - Productivity per ManHour (units/manhour)

LF - Labor Force (manhours/week)

DALF - Delay for Adjusting Labor Force (weeks)

Auxiliary equations represent relationships between levels. They are used to simplify rate equations. The hiring rate, for example, could be simplified by introducing the concept of labor force desired in an auxiliary equation.

LFD.K = SALE.K/PMH

HR.KL = (LFD.K − LF.K)/DALF

LFD - Labor Force Desired (manhours/week)

SALE - SALEs level (units/week)

PMH - Productivity per ManHour (units/manhour)

HR - Hiring Rate (manhours/wk/wk)

LF - Labor Force (manhours/week)

DALF - Delay for Adjusting Labor Force (weeks)

Two types of equations will be used to represent the delays in the system. These are distinguished as the first order delay and the third order delay. As seen in Figure B-1, the first order delay gives a maximum output at time zero whereas the third order delay does not reach a maximum output until later.

The first order delay is most often used for representing levels of awareness and for averaging variables in the system. The average sales, for example, could be represented by a first order delay.

ASALE.K = ASALE.J + (DT)(1/DASAL)(SALE.JK − ASALE.J)

ASALE - Average SALEs (units/week)

DASAL - Delay for Averaging SALes (weeks)

The third order delay, because it does not give a maximum output until later is most often used for representing delays such as the shipping delay. In DYNAMO notation a third order delay would be written in the following manner.

SR.KL = DELAY3(SS.JK,DRSA)

SR - Shipping Received (units/week)

SS - Shipments Sent (units/week)

DRSA - Delay in Receiving Shipments Average (weeks)

DELAY3 - A DYNAMO notation for representing a 3rd order delay

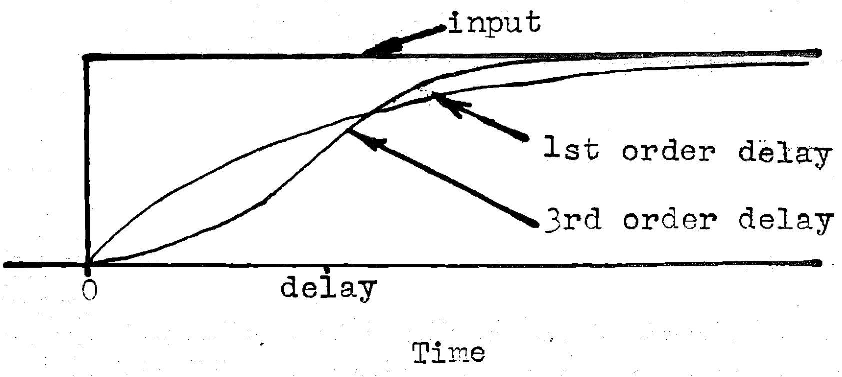

Figure B-1 The Time Response of the 1st Order Delay and the 3rd Order Delay.

Flow diagrams are used to help the reader come to a clearer understanding of the system. Visualizing the interrelationships of the system from a listing of equations is often very difficult. The flow diagram is used as a supplement to the written equations. Figure B-2 shows the symbols that will be used in flow diagramming.

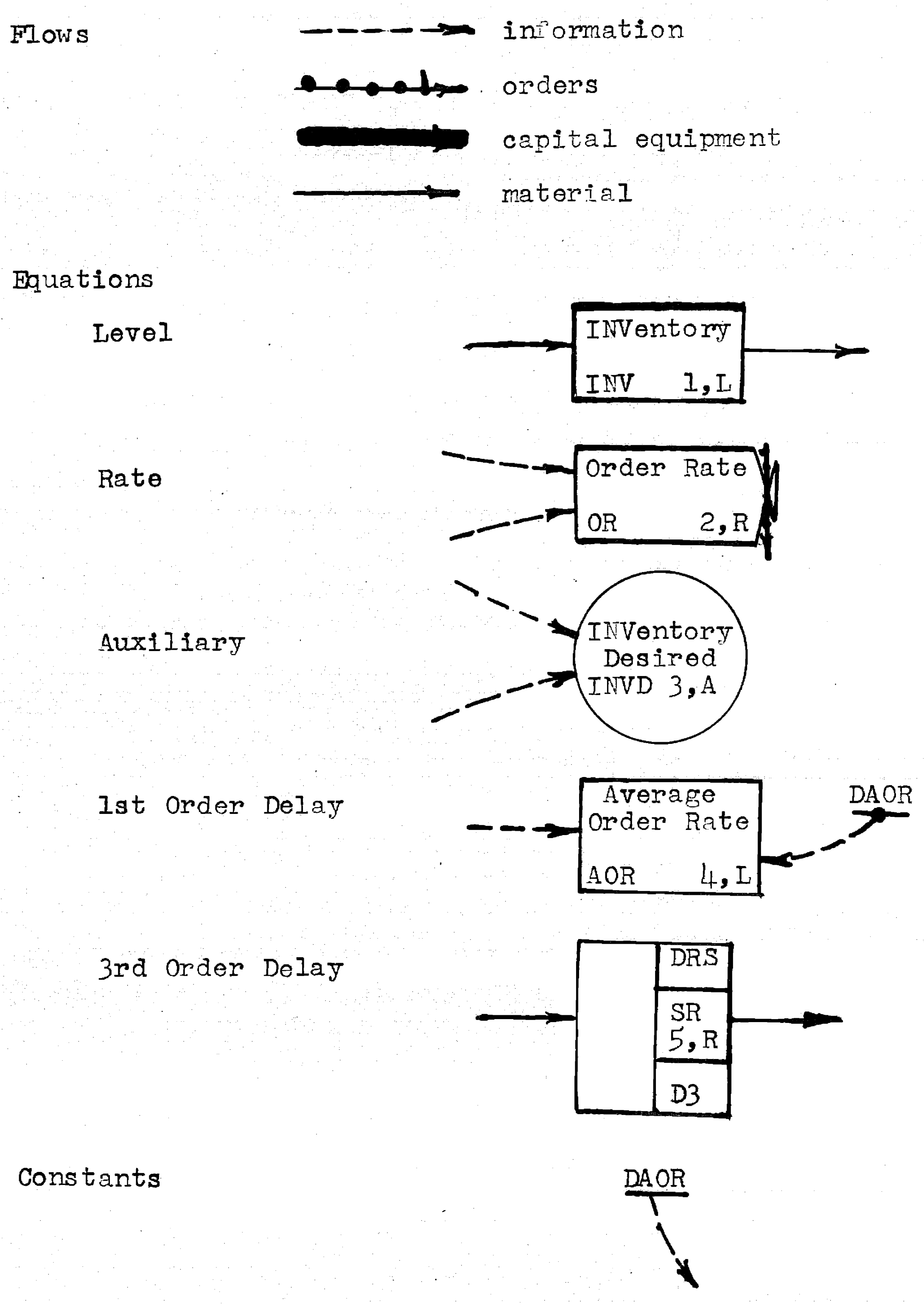

Figure B-2 Flow Diagramming Symbols.