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MANAGING R&D IN A HIGH-GROWTH COMPANY: the Significance of Coordinating People and Products

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The Problem

A number of high technology firms have recently reported increasing delays in the development of computer-related hardware and software. One such company, experiencing increasing product development times and schedule overruns, commissioned a system dynamics study of the management of its product development group. The purpose of the study has been to locate a range of potential sources for rising product development times in the company, and to identify aspects of the problem over which management can exercise some control.

Such product development problems are frequently blamed on exgoneous factors. The primary culprit is thought to be rising technological complexity--the increasing difficulty of designing and debugging the densely packed chips in very large scale intergated ciruitry (VLSI). Some might see the pattern as another instance of declining American productivity. Some in our client company placed part of the blame on the fierce competition for development engineers, which makes it difficult to meet hiring goals. And noting the tendency for growing firms to pass through periodic crises, some observers might suggest that corporate growth itself is to blame.

The system dynamics study described in this paper has identified two policy areas under management's control that have the power to produce rising product development times even in the absence of any increase in product complexity.

The Model

The model developed in the study captures in detail the structure of the company's product development group. It contains four main sectors: engineering manpower, managers, product development, and revenue and budget. There is sufficient structure to explore a wide range of issues relating to R&D productivity, including the assimilation and supervision of new personnel, the development of engineering and managerial expertise, competing demands for an engineer's time, tightness of the labor pool for engineers, and interactions between product development and the company's market and market share. Of central importance in the model are the endogenous representations of the decisions to introduce products for development, to hire engineers to carry out the work, and to acquire managerial structure to oversee the growing development group.

The model differs significantly from other system dynamics models of the R&D process in that it does not focus on the lifecycle of a single product development project. Rather, it traces over time a continuous stream of products and their average product development time. In addition, the model places the structure and behavior of the development process in the context of extremely rapid corporate growth.

Model Behavior and Policy Analysis

Our study indicates that the pattern of problems confronting the client company can be generated without assuming a number of the external factors some might feel are at the heart of the problems. It demonstrates that there exist rational and reasonable R&D management policies that can generate the problem behavior and alternative policies which can significantly improve the situation. Those policies deal with the general problem of coordinating the flows of engineers, managerial talent, and projects in the development group. The paper defines this notion of coordination and shows how weaknesses in coordinating flows can lead to the range of problems experienced by our client R&D group.

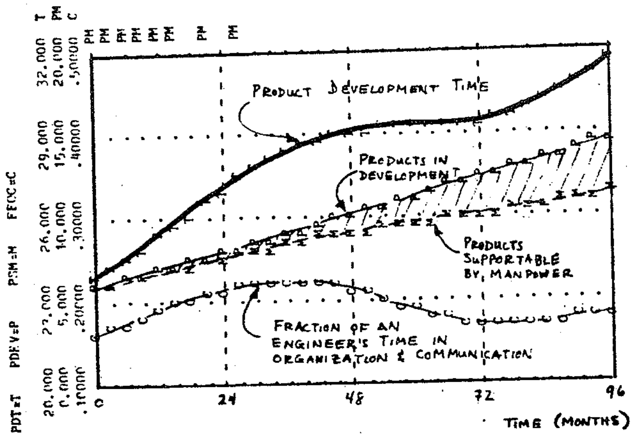
Figure 1 shows the pattern of rising product development times exhibited by the base run of the model. Also shown in the figure are two of the patterns in the model which lead to the rise. One cause is the widening wedge between products in development and products supportable by the number of engineers in the development group. The other is an oscillatory pattern in the fraction of an engineer's time devoted to organization and communication tasks, a mix of non-engineering activities necessary for the functioning of a product development group in a growing corporation. The widening wedge can permanently raise product development times and give the appearance of a gradual decline in engineering productivity. The oscillatory pattern creates ups and downs in engineering productivity that can cause short-term increases in product development times and schedule overruns.

Figures 2 and 3 show simplified views of the important feedback structures underlying these patterns. The paper analyzes these patterns, discusses the structure of R&D management policies responsible for them, and suggests how they can be countered by a careful coordination of people and products.

Figure 1: Base run behavior showing the pattern of rising product development time, together with graphs reflecting a lack of coordination of the flows of people and products in the R&D group.

Figure 2: Summary of feedback structure surrounding the decision to introduce a product for development.

Figure 3: Summary of feedback structure surrounding the decision to acquire managers in the development group.



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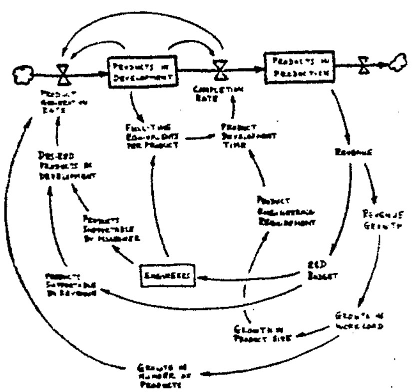

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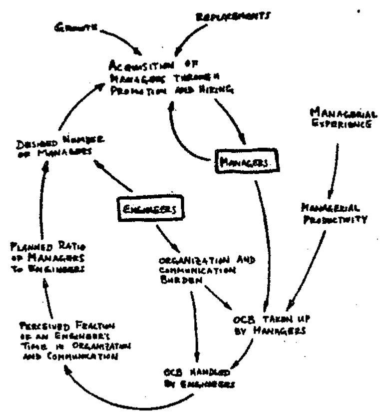

Figure 3: Summary of feedback structure surrounding the decision to acquire managers in the development group.

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I. Introduction

A number of high technology firms have recently reported increasing delays in the development of computer-related hardware and software. Experiencing increasing product development times and schedule overruns, one such company commissioned a system dynamics study of the management of its product development group. The purpose of the study has been to uncover potential sources for rising product development times in the company and to identify those over which management can exercise some control.

The results of the study are interesting to consider in light of current perceptions of declining industrial productivity in the United States and increasing question about the efficiency and effectiveness of research and development efforts. The study has demonstrated that the symptoms of what is apparently a problem of declining engineering efficiency of can be generated by a pattern of decisions in the firm. This paper describes the study that supports this conclusion and analyzes the decision structures that have the potential to produce rising product development times.

Section II of this paper describes in more detail the nature of the problems addressed by the study and discusses a number of perspectives on such problems. Section III describes the structure of the computer simulation model developed in the course of the study. Section IV analyzes the causes for rising product development times in the model. Section V discusses implications of these model-based analyses for the management of a development group in the context of rapid corporate growth.

II. The Problem

Our client company is a developer and manufacturer of data-communications equipment. Having enjoyed a real rate of revenue growth in the neighborhood of thirty-to-thirty-five percent per year for the past ten years, the firm now encompasses six diverse product lines, including high-speed modems, multiplexers, intelligent terminals, and diagnostic devices for computer communication systems. The firm projects that the personnel in the product development group will grow over the next five years at more than twenty percent annually.

Since 1977, the company has experienced increases in the time it takes to bring a product from the initiation of development to its first shipments. In this period overruns in product development schedules have increased in frequency and severity. Product development times have risen from a norm of 18-to-24 months to as high as 30 months, and schedule overruns have gone as high as nine months. In addition from 1977 to 1979 the company lost a number of senior development engineers. The reasons expressed varied considerably, but seemed to center on changes in the character of the firm brought about by its dramatically rapid growth: increasing administrative burdens on senior engineers, a large and growing percentage of new engineers in the development group, and the feeling that the quality and commitment of personnel were not quite what they used to be.

These two dynamic patterns, shown graphically in figure 1, are the focus of this study. It is reasonable to suggest that they are related: a loss of highly productive, senior engineers could easily set development projects back considerably. An influence in the opposite direction is also conceivable: a prolonged pattern of rising product development times could produce such a pressured atmosphere to meet schedule deadlines that engineers eventually opt for more comfortable job situations.

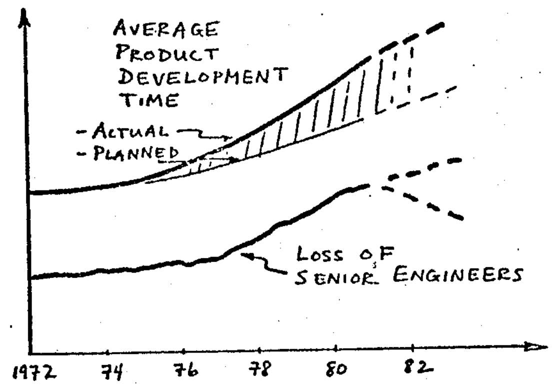

Figure 1: The problem focus: rising product development times and an increase in turnover of senior development engineers

Perspectives on the Problem

Such patterns may be viewed as natural, unavoidable aspects of the dynamics of rapidly growing, high-technology industries. A number of experts in the data-communications industry trace recent overruns in product development schedules to the shift to more sophisticated technology--from LSI (large-scale integrated circuitry) to VLSI (very large-scale integration). "At the heart of the problem," says Business Week [1], "are the complex logic circuits that make up the computer processor. As more and more of this circuitry is squeezed onto a single high-density chip, it becomes tougher to correct design flaws. Once the circuits are cased in silicon, they cannot be changed without redesigning and refabricating the entire chip, a process that takes at least four to six weeks." So product development times are seen to rise for two likely and related reasons: increasingly complex products inherently take longer to design, and undiscovered errors in the new VLSI technology take longer to correct. Fierce competition for development engineers skilled in LSI and VLSI design and manufacture is a natural consequence. Turnover is likely to be increasingly high, as engineers are lured from company to company by ever more attractive job situations. [2]

If the problems are industry-wide and essentially beyond managerial control, no one firm's share of the market is threatened by a pattern of rising product development times. Everyone will reach the market somewhat later than advertised, and no one will be able to capitalize permanently on the development delays of others. If, however, there are aspects of the phenomenon that are potentially within the control of corporate management, then those companies that learn the quickest stand to reap considerable benefits in market share and revenues. Our client company wished to investigate the point of view that some aspects of the problem could actually be exacerbated by its own R&D management policies. It requested a study focused internally on the operation of its development group.

An internal perspective leads naturally to a focus on engineering productivity, for it has an obvious effect on product development time:

$$\text{product development time} = \frac{\text{tasks in product development}}{(\text{engineers/product}) * \text{productivity}},$$

where a "task" is some arbitrarily defined unit of work and productivity is measured in tasks per person per unit time. It is thus easy to view a problem of rising product development times as a problem of declining engineering productivity per person. If fewer engineering tasks per month per engineer are completed, then even if the complexity of the development effort remains constant product development time will rise.

Management experience and the R&D literature suggest numerous factors have the power to influence productivity. Cotiis and Dyer [3], for example, discuss twelve dimensions of project management that correlate significantly with the efficient use of product development resources. Stahl and Steger [4] relate an engineer's productivity to characteristics of the individual and his or her development group. Allen [5] documents the role of communication networks. The notion of undiscovered rework, implicit in the above comments about the increasing difficulty of debugging VLSI circuitry, has been shown to have considerable power to cause schedule overruns in large projects. [6],[7] Our work thus focused initially on a range of productivity issues. A number of iterations through the modeling process produced the insight that is the central thesis of this paper: that what is apparently a problem of declining productivity can be generated by decisions within the development group that appear to be far removed from productivity concerns.

III. Modeling the Process of Product Development

A number of system dynamics models relating to the management of R&D projects have been developed and used for policy analysis. [6] - [11] The model in this study differs from these in that it does not trace the lifecycle of a single project; rather, it reproduces the dynamics of a development group over an eight year period as a continuous stream of products are developed and placed into production. The model focuses on the number of products under development, the use of resources required, and an aggregate average product development time. In addition, the model differs from past modeling efforts by placing R&D dynamics in the context of rapid corporate growth. It is intended to replicate the structure and behavior of a product development group growing initially at 25 percent per year.

As shown in figure 2, the model consists of four major sectors focusing, respectively, on engineers, managers, product development, and revenue and budget. The engineer sector (70 equations) traces the flow of engineers as they are hired into the firm, as they become assimilated and develop into highly productive senior engineers, and as they are promoted to managers or leave the firm. The sector monitors pressures that have the potential to cause quits of senior engineers and keeps account of competing demands for an engineer's time. The manager sector (23 equations) hires and promotes people into managerial and coordinating positions and traces the effects of managerial experience on the productivity of engineers. In the product development sector (29 equations) products are initiated, developed, completed, passed into production, and eventually drop out of production as they become obsolete. This sector computes an engineers' estimated product development time, the compromise target development time settled on in light of perceptions of market needs, and the actual product development time that results from the dynamics of the entire development group. The sales and revenue sector (30 equations) contains a simplified treatment of a growing market. The firm's market share responds to the quantity and quality of the firm's output, relative to its competitors. A percentage of the revenues from products in production is allocated to the development group and used for salaries and product development. With the market effects assumed in the model a closed loop of action and information exists: the operations of the development group affect revenues, and the resulting growth in revenues affects the growth of people and products in the development group.

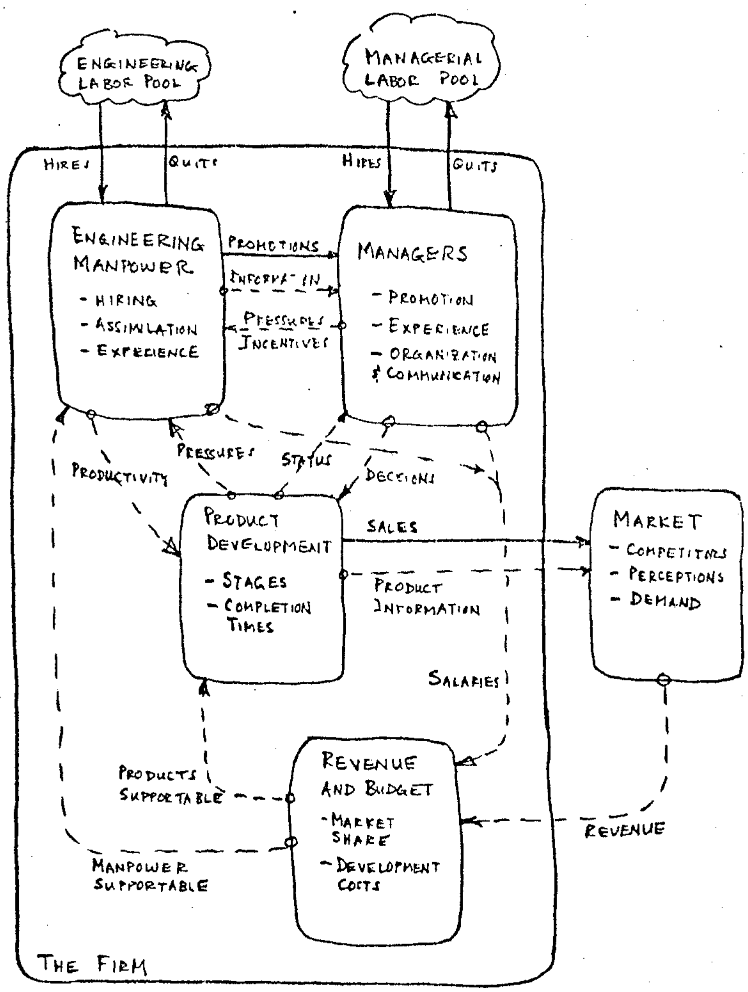

Figure 2: Overview of the structure of the model

The internal operations of the firm are influenced by three exogenous factors: a gradually growing pool of engineering talent, a growing market for the firm's products, and increasing competition for the firm's market share. These exogenous influences can be varied to test different scenarios. When kept the same in different computer simulations, they provide a common background against which to test different management policies within the firm. The dynamics of all of the remaining variables in the model are determined endogenously, that is, internally, by the assumed decision structure of the firm.

Three competing demands for an engineer's time are recognized in the model: engineering, supervising engineers new to the firm, and handling a mix of non-engineering activities called the "organization and communication burden" of the development group (described in section IV). To perform the necessary productivity computations the model introduces the concept of a "full-time equivalent experienced engineer," defined to be the mythical senior engineer who spends every minute of a working day in engineering activities. The computation is

FTEPP = ETS * EF * ESPP * EQEP * EIP

where

FTEPP = full-time equivalent engineers per product,
ETS = effective team size (people/product),
EF = engineering fraction (see below),
ESPP = effect of schdule pressure on productivity,
EQEP = effect of the quality of engineers on productivity,
EIP = effect of incentives on productivity (a policy parameter).

Essentially, the number of full-time equivalent engineers per product is equal to the actual number of engineers per product, multiplied by the fraction of these people that are "full-time, experienced equivalent engineers," and modified further by effects on productivity from short and long-term schedule pressure, the overall quality of the engineering group in the firm, and a potential effect of an incentives policy. The engineering fraction EF translates the number of inexperienced and experienced engineers in the model into an equivalent number of experienced engineers and subtracts out the fraction of time engineers spend in supervisory and organization and communication activities. The equation is

EF = EFEP - FEX*FMHS - FEOC

where

EF = engineering fraction,
EFEP = effect of fraction experienced on productivity,
FEX = fraction experienced,
FMHS = fraction of experienced manhours to supervision,
FEOC = fraction of an engineer's time in organization and communication activities.

Thus, six factors in the model affect engineering productivity: the basic quality of the engineering group, average aggregate engineering experience in the firm, supervisory activities required of engineers, team size, requirements for nonengineering activities related to organization and communication, and pressures arising from development schedules. Product development time is then simply the result of dividing the number of man-months of actual product engineering required by the number of full-time equivalent engineers:

PDT = PER/FTEPP

where

PDT = product development time (months),
PER = product engineering requirement (man-months),
FTEPP = full-time equivalent engineers per product (people).

Moving outward from productivity concerns, two concepts form the focal points for model conceptualization: accumulation processes -- stocks and flows of people and material -- and feedback loops -- closed paths of action and information. Figure 3 shows the principal levels (stocks) and rates (flows) assumed in the model. (A number of other accumulations that appear in the model as delays or averaging processes are not shown.) The model separates both engineers and managers into "inexperienced" and "experienced" pools so that a number of productivity effects can be represented. Supervision of new engineers by senior people, for example, creates two opposing effects on engineering productivity: increased supervision speeds the assimilation of new engineers and shortens their period of lower productivity, but it pulls senior engineers away from actual product development work. Both effects are captured in the model.

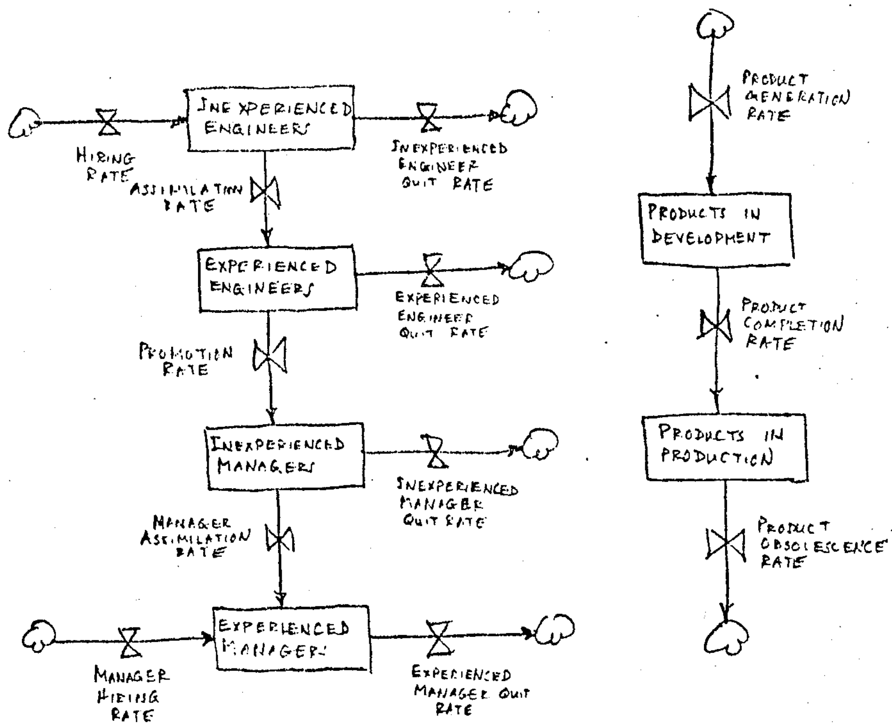

Figure 3: Principal levels (stocks) and rates (flows) in the model

The concept of feedback arises naturally in analyzing cause and effect sequences that appear to be related to the problems of rising product development times and increasing quits of senior engineers. Considering supervision once again, suppose the firm experiences an increase in quits among senior engineers who spent some fraction of their time providing engineering guidance to others. The loss would mean that less day-to-day supervisory time would be available to newer engineers. As a consequence, it should take longer to assimilate new engineers into the firm -- a longer apprenticeship or development period before a new person reaches the productivity of a senior engineer. Thus, the rate of flow into the pool of experienced engineers would tend to slow up. In sum, an increase in the outflow from the experienced pool tends to decrease (other things being equal) the inflow to that pool, further exacerbating the drop in senior engineers caused by the increase in quits. This self-reinforcing process, called a positive feedback loop, is shown in figure 4.

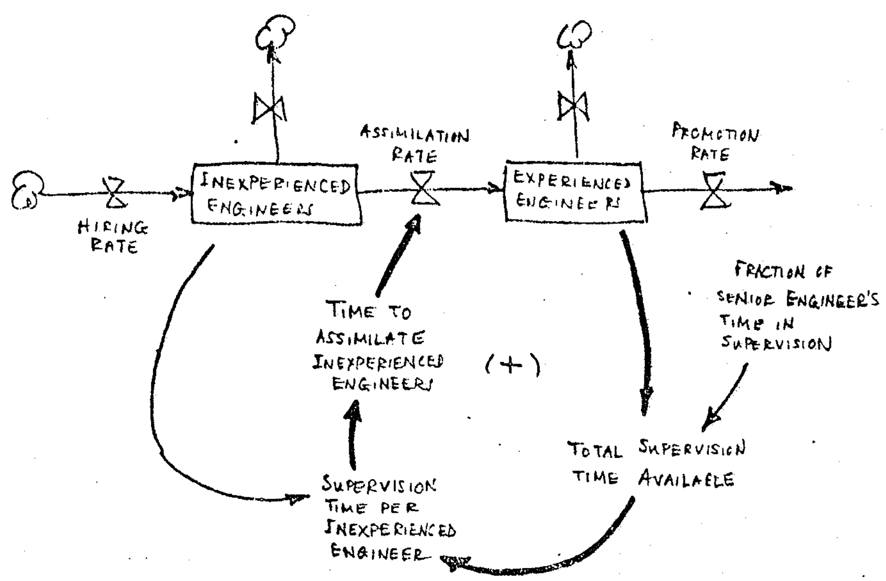

Figure 4: Self-reinforcing (positive) feedback loop in the supervision of new engineers by senior development engineers.

The feedback perspective illuminates two general types of processes at work in any complex system -- those that are self-regulating and those, like the supervision loop, that are self-reinforcing. The model in this study was formulated from the point of view that all decisions are made in the context of feedback. Some aspect of the system is perceived; change comes from the desire to move the system closer to some desired state; decisions are made to bring the actual state of the system closer to the desired; the actions taken alter the state of the system, giving rise to new perceptions of the system. Such a closed loop of action and information is called a feedback loop, because information eventually "feeds back" to its point of origin, affecting future perceptions and actions. The model developed in this study contains hundreds of such loops. The dynamic behavior of the system is a consequence of the complex interactive structure they form.

The decision to introduce a product for development illustrates a number of such feedback patterns, and is an important determinant of the behavior of the system over time. The decision is based upon the current workload in the development group, the availability of resources, project completions, and growth goals. The model equation states:

PGEN = (DPDEV-PDEV)/PDEVAT + COMP + GP*PDEV,

where

PGEN = product generation rate (products/month),
DPDEV = desired products in development,
PDEV = products in development,
PDEVAT= adjustment time for products in development (months),
COMP = product completion rate (products/month),
GP = growth factor for products in development.

Essentially, the equation states that new products are added to the workload of the development group when old ones are completed (COMP) and when additional ones are necessary to keep up with planned growth (GP*PDEV). The term (DPDEV-PDEV)/PDEVAT represents pressures in the decision process that adjust the rate of introduction of new products to the availability of development resources. It adjusts the actual introduction of products above or below the base rate (COMP + GP*PDEV) depending upon how PDEV compares to its desired value, DPDEV. The latter is an aggregate concept representing the firm's perception of the number of products in development that is necessary to meet its market needs and that can be supported by the manpower and revenue currently available to the development group. The parameter PDEVAT reflects how closely management monitors the workload in the development group and how rapidly it takes action to bring actual conditions more in line with desired. In the base case in the model PDEVAT is set at 24 months, the average product development time at the start of a simulation.

A feedback loop is evident in the first term in this formulation. The current number of products in the development group (PDEV) is compared to a desired number (DPDEV). Any discrepancy generates countervailing action in the product generation rate: if PDEV is too small, for example, the adjustment term will be positive, and more products will be generated per month until PDEV is brought up to DPDEV. Figure 5 shows the simple feedback loop represented by this adjustment term. The loop is self-regulating: it continuously strives to adjust PGEN to keep the number of products in the development group equal to the number desired. It is called a negative feedback loop because it tries to negate or counteract any change in PDEV from its goal, DPDEV.

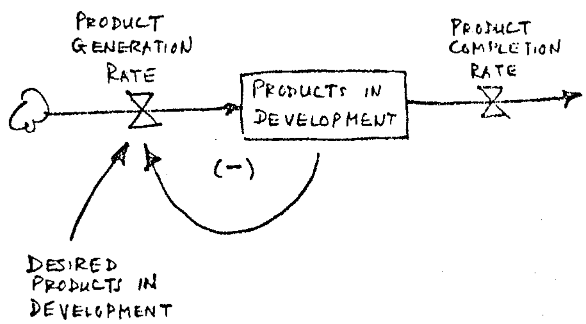

Figure 5: Self-regulating (negative) feedback loop in the decision to introduce products for development

The formulation of PGEN also illustrates a positive or self-reinforcing feedback loop. The positive feedback loop linking products and revenue and is among the most important self-reinforcing feedback loops associated with a technology-based company. Products in development eventually become products in production, which are the source of the company's revenues. Revenues support the budget of the development group: the more revenues generated, the more engineers, money, and technical resources are available for further product development. In the model, more revenues thus mean a higher number of products supportable in the development group, that is, a higher DPDEV, and hence a greater rate of product generation. The fundamental growth-producing loop of a technical company involves cummulative expansion of products and revenues: more products in development lead eventually to more products in production, which produce more revenue; more revenue means more resources for product development, which lead to more rapid generation of products and a growing stock of products in development.

This closed sequence of causes and effects appears as three loops in figure 6. Each is clearly self-reinforcing: by generating additional revenue products in development usually lead to still more products in development. In unfortunate circumstances each loop in figure 6 can be self-reinforcing in a catastrophic direction, when products in production produce declining revenues, leading to fewer resources available for product development, leading to a cutback in products in development, eventually fewer products in production, and still greater declines in revenue.

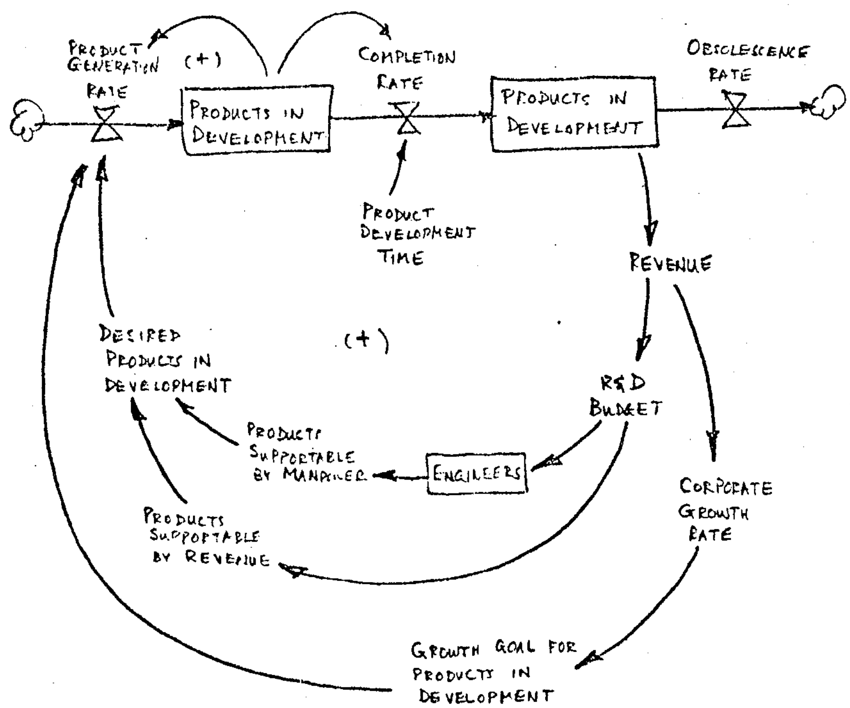

Figure 6: Self-reinforcing (positive) feedback loops in the decision to introduce products for development

The model contains more than 150 equations representing a complex structure of interacting variables and interconnected feedback loops assumed active in a corporate product development group. It was constructed over the course of a year with the aid of the senior director of business planning in our client company in consultation with the vice president for development and a senior director of development. A complete description of the model is not possible here. [12] Instead, in the following discussion of the behavior exhibited by the model, those pieces of model structure that support the insights it has helped to generate will be presented in detail.

IV. Analyzing Rising Product Development Times

The base run of the model replicates the problem behavior of our client company. Figure 7 shows a pattern of rising product development times set against the engineers' projections, management's desired product development time (assumed constant at 24 months), and the compromise upon which engineering and management decisions are based. Figure 8 shows the the fraction of senior engineers leaving the firm each month, along with the three quit pressures generated endogenously in the course of the simulation. We ultimately want to know why product development time is rising, but figure 7 prompts the question of why it stops rising for two years in the middle of the simulation. Figure 8 suggests that the burst in quits of senior engineers is related to the quit pressure from the "administrative burden" -- a notion linked to the concept of the organization and communication burden mentioned above and described in more detail below. But why the rise and fall in that quit pressure?

The simulation model is a laboratory tool. By altering parameters, changing the strengths of assumed effects, or deactivating pieces of model structure we learn the connections between model structure and behavior. Such experiments are simple in the model and impossible in the real system. With care, and a number of iterations of conceptualization, formulation, testing, and refinement, we try to move toward understanding the connections between the structure of the real system and its behavior.

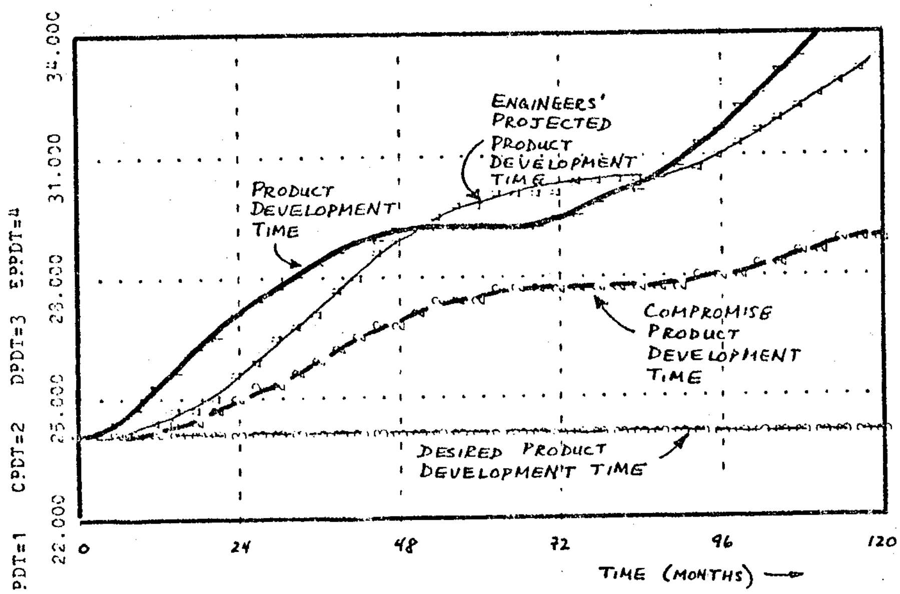

Figure 7: Product development times in the base run

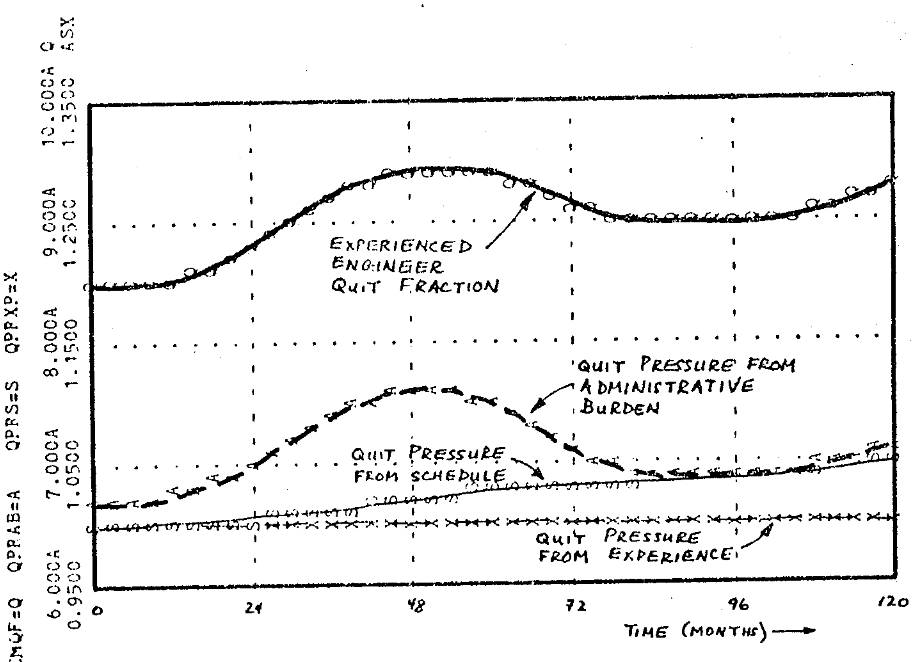

Figure 8: Quits and quit pressures in the base run

As a result of such an iterative modeling process, we can pinpoint directly the causes of the model behavior shown in figures 7 and 8. The pattern of rising product development times (PDT) can be traced to two relatively independent sources. One has the capability to push up PDT almost indefinitely; the other generates fluctuations in engineering productivity that translate into relatively short-term ups and downs in PDT. The cyclic pattern is due to the way the organization and communication burden is handled as the firm grows. The long-term pressure upward on PDT actually comes from the structure of the decision to introduce a product for development. Figure 9 shows the behavior over time of several of the variables underlying these pressures on PDT.

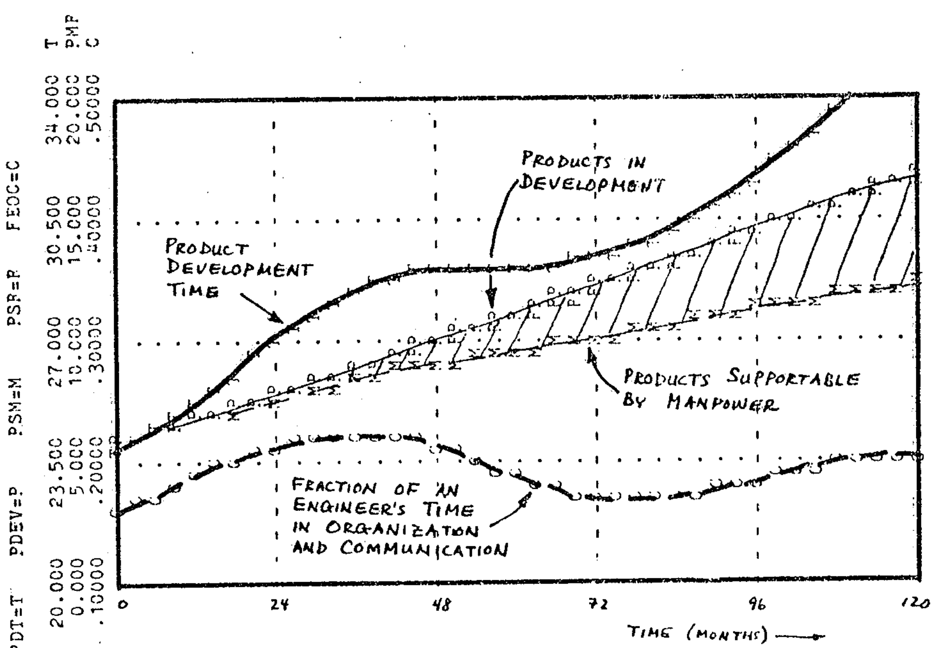

Figure 9: Underlying causes of rising product development times in the model

Products Supportable in the Development Group

Corporate officers in our client company described a lengthy process leading to the decision to develop a product. It begins with a comprehensive five year corporate plan that forms the framework for yearly planning. Anticipated revenues, the behavior of competitors, availability of corporate resources, the market for the firm's products, and more, all figure into planning for a sequence of product revisions and new product developments. Plans are reconsidered each year in light of then current conditions and projections. Orders for the necessary additional engineering manpower are formulated accordingly and then updated quarterly in light of available revenues and the availability of engineering manpower outside the firm. In the model that description is represented in the formulation for the product generation rate, PGEN.

The critical features of the decision represented by PGEN are the formulation of desired number of products in development, DPDEV, and the basic growth rate of the number of products under development, GP. The model computes DPDEV by first computing the number of products supportable given the number of engineers in the development group and the number of products supportable given the trend in revenues. These two figures are brought together to determine DPDEV, as follows:

$$DPDEV = PSR * f(PSM/PSR)$$

where

DPDEV = desired products in development,

PSR = products supportable by revenue,

PSM = products supportable by manpower,

and f is a function chosen to reflect whatever biases are inherent in the decision in the client company (and probably many others). Perhaps the most rigidly rational policy would chose f so that DPDEV is the minimum of PSR and PSM, but that is not likely to be the case in actual practice. The bias in DPDEV in the model is to lean slightly more toward PSR and to downweight PSM if the revenue stream suggests more products than the current number of engineers can easily handle. (The shortage of development engineers and the fierce competition for them means that PSM is almost always less than PSR.) The model formulation attempts to capture the tendencies to start a project somewhat before the full team of engineers has been assembled. It reflects existing pressures to reassign people somewhat prematurely from projects that are winding down and to shift people off long-term projects to deal with short-term product refinements, all with the assumption that extra effort and talent can bring the projects in on time.

The growth in products in development, determined by the term GP*PDEV and responding to long-term corporate growth goals, has a similar potential to push more products into the development group than the engineers can comfortably handle. The model computes a growth factor for the total workload in the development group, setting it equal to a growth target, GT, the long-term growth trend in revenues. That growth in workload is then allocated by decisions internal to the model (and the company) into a growth in the size or technical complexity of products and a growth factor for the number of products, GP. In periods of accelerating revenue growth, GP will tend to be less than the growth rates of revenues and people in the development group, so the group catches up to its workload. In periods of decelerating revenue growth, however, the company in the short-run tries to continue growing at its traditional rate, and the growth in products in the development group will tend to be slightly greater than the growth in manpower.

Combined, the policies determining the number of products supportable in the development group and the basic growth rate of the number of products under development lead to the widening wedge between PDEV and PSM shown in figure 9. In spite of increases in productivity that the model assumes as schedule pressure increases, too many products under development lead to inexorably rising product development times.

Such a conclusion is hardly remarkable. But the fact that policies associated with the decision to initiate a product development project can cause problems that look like declining productivity was a revelation to our client company. Midway through the project, a senior director of development estimated that the group had been ten to fifteen percent understaffed since at least 1977 because of the shortage of engineering talent. Yet that was not seen by many as even a potential contributor to rising product development times. Corporate management leaned toward such cures as incentives policies, corporate reorganizations, and improving engineering communication channels to cope with the problem.

Policies aimed at improving productivity that do not address the underlying problem described here may work in the short run but will fail in the long run. Suppose, for example, that a dramatically successful incentives gram creates a permanent ten percent increase in engineering productivit. A reasonable expection would be that product development time should rapidly fall about ten percent, the amount of the productivity increase. Tracing around the feedback loops shown in figure 6 one sees that products would flow quicker into production, revenue and revenue growth would rise, profits would rise, leading to an increase in the R&D budget, and the product generation rate would eventually rise in response, producing more products in development. With the higher productivity the firm would enjoy higher revenues, but the tendency to overextend the development group would remain, and product development times would rise back up as a result. The feedback structure of the system compensates naturally for the increase in productivity that stems from the incentives policy. The notion of compensating feedback is one of the important insights of the feedback perspective on the behavior of complex systems. [13]

The Fraction of an Engineer's Time in Organization and Communication Activities

A growing "organization and communication burden" is responsible for the cyclic pattern shown in figure 9. As each engineer spends a greater fraction of his or her time in non-engineering activities, less productive engineering time is available and product development times should rise as a result. Conversely, if less time is spent in non-engineering activities, product development times should fall. The model exhibits a recurring up and down cycle in the fraction of time an engineer spends dealing with the organization and communication burden of the development group. Consequently, there is alternating upward and downward pressure on PDT.

The organization and communication burden, OCB, is a highly aggregated concept in the model representing a mix of nonengineering activities assumed to be required in the normal operation of a development group. We intend the concept to include such things as reporting, coordinating members of a team, coordination between teams, budget preparation, scheduling, ordering materials, handling crises, interviewing and hiring, evaluation for salary and promotion decisions, and so on. It is a range of tasks including many commonly considered managerial. No attempt was made to model the detailed interactions OCB is intended to represent. OCB is formulated simply to rise slightly more rapidly than the total number of engineers in the development group:

$$OCB = a*(TM^{b})$$

where

OCB = organization communication burden (man-months per month),
TM = total engineering manpower (people),
a = proportionality constant to set initial conditions,
b = an exponent slightly larger than 1.

(The exponent b used in the above runs was 1.2.) The final section of this paper discusses variations on the formulation for OCB.

The model assumes that a certain amount of the organization and communication burden must be handled by engineers. Fifteen percent of an engineer's time is deemed acceptable in the model. When it is perceived that engineers are forced to devote more than that to these nonengineering activities, pressures build to speed the acquisition of more managerial people. The primary role of managers in the model is to draw off the burden of organization and communication activities from engineers, increasing their productivity by leaving them freer to engineer.

The cyclic pattern in the fraction of an engineer's time in organization and communication activities can be traced to a set of negative feedback loops and perception delays involved in the decision to acquire managers. The equation for the acquisition of managers has exactly the same basic structure as the equation given above for the product generation rate: it contains a term to replace quits and retirements, a term for growth, and a short-term adjustment to keep the number of managers equal to the number desired. Figure 10 shows an overview of the structure assumed in the model. Essentially, managers are promoted or hired in a planned ratio to the number of engineers in the development group. As it is perceived that engineers are spending too great a fraction of their time in nonengineering activities, the company deliberately changes the planned ratio of managers to engineers to correct the situation and return the development group to full productivity.

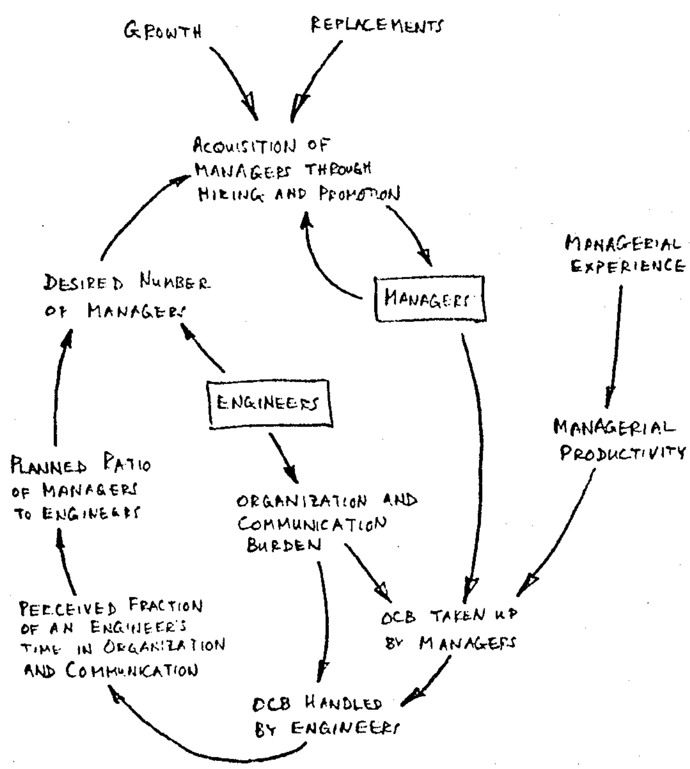

Figure 10: Structure underlying the cyclic pattern in the fraction of an engineer's time in organization and communication activities

There are several rather unavoidable delays around the large negative loop shown in figure 10. It takes the engineers themselves some time to realize that the time they can devote to engineering has gradually declined. Top management takes even longer to come to the conclusion that past operating policy should be changed and then change itself takes time.

The loop can be thought of as representing some aspects of organizational change: a change in the ratio of managers to engineers probably represents in reality a shift to another layer of management, or to a matrix structure, or from matrix to product line organization. These various perception and action delays around the negative feedback loop tend to produce a natural oscillating pattern in FEOC, the fraction of an engineer's time in organization and communication.

The sequence of events is as follows: the burden of organization and communication activities grows slightly more rapidly than the development group. Additional managerial structure is acquired in proportion to the growth of the group, but because OCB grows faster the planned ratio eventually proves to be too small; the fraction of an engineer's time in organization and communication activities, FEOC, grows. When it is finally perceived that productivity is suffering from having engineers deal with various nonengineering activities, steps are taken to increase the planned ratio of managers to engineers and speed the acquisition of managers. The planned ratio continues to increase until PFEOC, perceived FEOC, has returned to an acceptable level. The delay between FEOC and PFEOC guarantees that for PFEOC to fall to the acceptable fifteen percent level FEOC will drop even further. Excess managerial capacity is acquired, and the group profits from considerably increased engineering productivity until further growth pushes it into a repeat of the cycle. The pattern is reminiscent of the corporate evolutions and revolutions discussed in the literature. [14],[15]

One result of this ebb and flow of group reorganization is periodic upward and downward pressure on product development times. It coexists with the insistent upward pressure on PDT that stems from the widening wedge (discussed above) between products in development and products supportable by manpower. The graph of PDT shown in figures 7 and 9 is thus the result of two patterns superimposed. The rise in PDT exhibited by these simulations of the model is not a consequence of a rising technical complexity or an increasing number of man-months or product engineering required (PER), although PER is rising throughout the simulation. Rather, the schedule overruns and rising product development times result from natural tendencies and perceptions in the decision structure of the firm.

We can verify these conclusions by simulating the model with revised policies in product generation and the acquisition of managers. In model terms the pattern of rising product development times shown in figures 7 and 9 is essentially eliminated if DPDEV (desired products in development) is set equal to the minimum of PSR and PSM (products supportable by revenue and manpower, respectively), PDEVAT (product development adjustment time) is reduced from 24 months to, say, 6 months, the time to perceive FEOC is reduced from 18 months to, say, 6 months, and the planned ratio of managers to engineers is set to respond more quickly to values of PFEOC above the acceptable fifteen percent level.

V. Policy Implications

The parameter changes described above represent improved coordination between the flows of people and products in the development group. Revising DPDEV as described in the previous paragraph amounts to trying harder to match the amount of work to the number of engineers in the development group. If market needs and the revenue stream suggest the initiation of a product development effort but the firm can not hire engineers fast enough, the revised policy says to hold off until an appropriate team can be assembled. Shortening the adjustment time PDEVAT means that more attention is paid to any discrepancies to desired and actual conditions, and action to correct them is taken sooner. Management listens more and responds more quickly to claims of an overload of work emanating from the development group. Perhaps a formal monitoring system (designed to add only minimally to the organization and communiction burden) is implemented. The parameter changes shortening the delays and reaction times in the acquisition of managers can be interpreted similarly. In both areas of the system the effort is to get enough people to do the job and -- the other side of a loop -- to adjust the growth in workload, if necessary, to match the people available.

The goal of the analyses in section IV is eventually an increased understanding about the relationships between structure and behavior in the real product development group. The critical question for model-based analyses is their transferability: to what extent should we believe that policies that work in the model will work in reality? The answer hinges on our confidence in the degree of match between the real system and the model.

While we might agree that it is the matching of essentials, not the congruence of all details, that is required, the extremely high level of aggregation involved in the formulation of the organization and communication burden, OCB, is a potential source of a lack of confidence in the model-based analyses. Current work is exploring formulations that compute OCB as a function of product team size (people per product) as well as the total size of the development group. Our client company believes that team size has a significant effect on OCB; they estimate that a doubling in the average size of a product development team (other things being equal) would increase OCB more than a doubling in total engineering personnel (other things being equal).

Experiments with reformulations of OCB indicate that matching the number of managers to the size of the task they are supposed handle is rather subtle. In these reformulations we have assumed that it is not possible for a company to directly perceive the size of the organization and communication burden; it must be inferred from the number of people enaged in it and the extent of their effort. The company must try to match the growth of its managerial staff to the growth of an assumed or inferred organization and cummunication burden. Although these investigations are incomplete, the behavior of the model under the reformulations remains much the same as shown above. Again, a fundamental negative loop with perception and action delays surrounding the acquisition of managers tends to produce an oscillatory pattern in the time an engineer spends in these nonengineering activities. While some of the details differ, the basic structural insight remains unchanged.

The analyses in IV have deliberately simplified model structure and behavior, much as the model deliberately simplifies the structure of the real system. Other pieces of structure in the model (and the real system) have the power to push up product development times. The increasing difficulty of finding and correcting design errors in VLSI can increase product development times by lengthening the time involved in rework. [6],[7]. Mistakes in estimating the extent or complexity of a product development effort can lead to assembling too small a team and obviously cause overruns in a project schedule. The model shows that a sharp increase in the corporate growth rate and the hiring of new development engineers can push up product development times in the short run by decreasing average productivity per engineer and increasing the time senior engineers devote to supervision. The escalation of salaries in the industry tends to cause the range of engineers' salaries in a company to compress over time; if uncorrected, salary compression can lead to disgruntlement and departure of senior engineers and a consequent drop in aggregate average productivity. Our simulations indicate that it might even be possible for the company to promote such a number of senior engineers into management that engineering productivity could not keep up with corporate growth; product development times can rise as a result of the development group's promotion policy.

Faced with rising product development times, a company thus has a wide range of policy areas and procedures to reconsider. By emphasing policies associated with product generation and the acquisition of managerial talent, this paper suggests that the range of policy options to consider is broader than previously thought. The analyses in section IV should not be interpreted as a claim that weak coordination between the flow of people and products is the sole cause of the problems. However, if present, weak coordination is an extremely powerful source of rising product development times and the problem symptoms (such as increasing quits) that can follow as consequences. Because of its importance and the relatively low cost associated with the monitoring required to improve the situation, the coordination of people and products should be considered near the top of a policy check list designed to halt rising product development times.

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